DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES

PART III: DEVELOPING CRITICAL TECHNOLOGIES

SECTION 1: AERONAUTICS TECHNOLOGY

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Defense Threat Reduction Agency
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SECTION 1—AERONAUTICS TECHNOLOGY

Scope

Highlights

- The advanced technologies listed have been chosen because they will reduce weight, vulnerability, accident rates, and operating and support (O&S) costs while providing increased reliability, maneuverability, and overall performance.
- Emphasis on uninhabited systems is increasing.

OVERVIEW

This section covers technologies associated with aerodynamics, propulsion, structures, vehicle control, subsystems and components, and design and integration that might be used in various aeronautics systems. Future aeronautics systems include fixed-wing aircraft, rotary-wing aircraft, hybrid vehicles, uninhabited air vehicles, and any other airborne vehicle that could be used for a military mission.

This section does not address specific vehicles; rather it addresses the technologies used in multiple vehicles or revolutionary new concepts, such as blended wing/body (BWB) and micro air vehicle (MAV). It also does not address space vehicles (see Section 19), but it does cover vehicles that would operate with aircraft-like efficiency, put payloads into orbit, return to earth, and launch again with minimal support.

Several current air-vehicle missions—strategic bombing, air mobility, attack, air superiority, reconnaissance (intelligence gathering), and special operations—will endure for the foreseeable future. In addition, air vehicles may be required to access space on-demand in support of space operations. Air vehicles will need speed, range, lethality, flexibility, and survivability to accomplish these missions.

Advanced aeronautics technologies are expected to provide a decrease in vehicle weight, with an attendant increase in range or payload; an increase in reliability; an increase in maneuverability; a decrease in vulnerability; a decrease in accident rates; a decrease in O&S costs; and a decrease in acquisition costs. In the future, the military will place more emphasis on using unmanned military systems to augment manned military systems. This will include unmanned combat aerial vehicles (UCAVs) for the suppression of enemy air defense and strike missions and MAVs for reconnaissance.

Affordability is a key issue for future aeronautics technologies. On the commercial side, few customers are willing to pay the price for new technology unless it provides a dramatic improvement in the cost of operations. Most developmental work is limited to incremental improvements—much of it focused on reliability, maintainability, and operability. Much work is being done to package existing technologies in new ways and increase capabilities with advances in computational capability. Military systems are increasingly relying on adapting commercial-off-the-shelf (COTS) technologies for mission uses. This is a trend that has occurred recently and is expected to continue in the future as military budgets are pressured.

Unmanned aerial vehicles (UAVs) offer the potential of unique capabilities (size, maneuverability, and agility not constrained by human performance and life-support needs) while also providing cost savings. For the most part, technologies are the same except when they fly beyond manned vehicle operational envelopes. MAVs present technological challenges in miniaturizing components (e.g., actuators, motors, and sensors).

Modularity in vehicle design could be used to provide mission flexibility and extend vehicle life via upgrades and modifications. The benefits would be found at several levels of the production and operational areas. These could include design, manufacturing, flight line, intermediate, and depot maintenance.

Improvements in vehicle and manufacturing process design methods offer the potential for decreased manufacturing cost and design optimization. Advanced composite materials could contribute to a decrease in weight while still providing adequate structural integrity and performance. Reliability can be enhanced with an increased application of electric power while decreasing the use of hydraulics.

Speed of military response can be realized by extending the range and payload of large aircraft. Large (million pound) transonic aircraft with an unrefueled range of 12,000 miles will be possible in the next quarter century. The military might leverage the commercial transport market for its airlift needs. A hybrid airship is being developed to carry extremely large payloads. The half-blimp, half-airplane could fit the lift niche between large transports (Boeing 747 and Lockheed C-5) and ships. Dubbed "Aerocraft," it is expected to get from the United States to Europe in less than a day. It would haul 1 to 1.5 million lbs at 125 knots and be about 780 ft long.

Although many future developments will be evolutionary rather than revolutionary, work is underway on projects that go beyond current vehicles, applications, or principles. The charter of the National Aeronautics and Space Administration (NASA) emphasizes the exploration of high-risk technology areas that can revolutionize air travel and create new markets for U.S. industry. The technology challenges for NASA include eliminating the barriers to affordable supersonic travel, expanding general aviation, and accelerating the application of technology advances. NASA and its industry partners developed a concept for a high-speed civil transport (HSCT) that would fly 300 passengers at more than 1,500 miles per hour (more than twice the speed of sound) at a ticket price less than 20 percent above comparable, slower flights. The HSCT was being developed as part of NASA's High-Speed Research (HSR) program begun in 1990. Although the international economic stakes were envisioned as being high (markets were projected for more than 500 HSCTs between 2000 and 2015), the HSR program was cancelled in 1999 because of changes in the aircraft market and industry interests. The lack of financial participation by the major aircraft manufacturers was the driving factor for cancellation. This industry action was the result of market analyses and technology requirements assessments that indicated an HSCT cannot reasonably be introduced before the year 2020.

Lawrence Livermore National Laboratory (LLNL) is working on a new design for a hypersonic aircraft. The "HyperSoar" (see Figure 1.0-1) would fly at Mach 10 and would "skip" along the edge of Earth's atmosphere. After ascending to approximately 130,000 ft just outside Earth's atmosphere, it would turn off its air-breathing engine and coast back to the edge of the atmosphere. There, it would quickly start its engines and "skip" back into space. This maneuver would sharply cut heat build-up on the frame, a problem that has inhibited previous hypersonic designs. Potential military benefits would be cargo delivery or strikes from altitudes and airspeeds that could not be defeated by current defensive measures.

Figure 1.0-1. HyperSoar

RATIONALE

Air vehicles will play a significant role in dominant maneuver, one of the four operational pillars of Joint Vision 2010. U.S. forces will have to engage in numerous actions around the globe. Power projection will be achieved through rapid strategic mobility. Air mobility will be required to respond to developments quickly and with sufficient force to stabilize crisis situations. Long-range precision capability, combined with a wide range of delivery systems, is emerging as a key factor in future warfare. Enhanced standoff capabilities will provide a wider range of delivery options.

On risky missions, the UCAV would fly 40 or more miles in front of manned fighter jets to knock out air defenses. Loaded with low-cost precision bombs, a fleet of UCAVs commanded by controllers from a home base could wipe out anti-aircraft guns and missiles on the ground. This would protect manned assets and leave them for missions for which the UCAV cannot be used. The UCAVs must remain in contact with their remote commanders through complex communications links that must be safe from enemy signal jamming. Production of battlefield versions—at $10 million per UCAV—could begin in 2004. Dozens of the jets could be available by 2010, much sooner than military projections of just a few years ago. UCAVs offer an attractive mix of operational need and economic necessity. Reusable unmanned vehicles could deliver precision ordnance that is less expensive than cruise missiles. Since most concepts entail a system that remains in storage until needed, savings would be realized through reduced operations and training (needed for manned systems). Operator training would be conducted in simulators. A potential reduction in search and rescue forces would provide additional savings.

TECHNOLOGY ASSESSMENT

Aeronautics systems will benefit from advances in aerodynamics, propulsion, structures, vehicle control, subsystems and components, and design and integration technologies. UCAVs will be aggressively pursued because of budgetary constraints, manpower limitations, and technical maturity. They represent a challenge in systems integration and systems development. Advances in computer technology, communications, flight controls, and global positioning make UCAVs possible and will add to the capabilities of manned aircraft. The reader will not find a technology called “UCAV” herein, but many of the technologies listed apply to such vehicle systems.

WORLDWIDE TECHNOLOGY ASSESSMENT (see Figure 1.0-2)

The United Kingdom is investigating several new technologies for its Future Offensive Air System, which is expected to enter service around 2017 as a replacement for the GR4, ground-attack Tornado. A manned aircraft is one of three options being considered to provide the required capabilities. Unmanned aircraft and cruise missiles will also be evaluated. Technology and affordability considerations will be the main drivers of cooperation with other countries.

In France, Dassault is evaluating a light combat aircraft concept called the Futur Avion de Combat Europeen (FACE). This future (perhaps tailless) European combat aircraft is envisioned to complement the Rafale and the Typhoon in a “high-low” mix like the F-22/JSF.

Russia is continuing to develop technology demonstrators with several thrust vectoring aircraft (SU-37, MiG-1-42/1-44) and one with forward-swept wings (S-37). The MiG-1-44 was the prototype for a competitor aircraft for the U.S. F-22. The MiG-1-44 made its long-delayed maiden flight on February 29, 2000. It is designed to be super maneuverable (maintain steering at angles of attack of 60–70 deg). Preliminary work on this aircraft was begun in 1983, and indications are that it could be replaced by a fifth-generation aircraft that will replace the MiG-29. The aircraft is expected to compete with the U.S. Joint Strike Fighter (JSF). Funding constraints have caused severe slippages in Russian aircraft programs. Meager funding, a small procurement budget, and the reported inability of the Russian manufacturing base to produce aircraft in any quantity dictate a time period of 10–20 years to accomplish an aircraft program.

China is developing the J-10, which is the weight and class of the Eurofighter 2000. It is similar to the Israeli Aircraft Industries (IAI) Lavi multirole fighter and is expected to be operational by 2005. The XXJ will follow around 2015.

Australia is developing a fixed-wing aircraft with vertical/short takeoff and landing capabilities. The aircraft has a fan in the wing and one in the rear. Sadleir Technology & Innovation Co. PTY, Ltd., envision a 450–600 seat airliner.

EUROFAR, a consortium of Aerospatiale, Eurocopter France, Eurocopter Germany, and GKN Westland (United Kingdom), is developing a European tilt-rotor aircraft for regional airlines. The first flight is expected in 2004, with entry into service scheduled for 2010. Another international effort—a BWB, ultrahigh-capacity airliner/very large commercial transport (UHCA/VLCT)—involves Aerospatiale (France) and Daimler-Benz (Germany).

Japan's endeavor is the F1-X, a follow-on to the F-15J. This aircraft has thrust vectoring nozzles, digital fly-by-light (FBL) controls, co-cured composites, and radar absorbing materials (RAMs). Airbus is planning to develop the A3XX, a long-range, double-decker, jumbo jet that could seat between 500 and 600 passengers.

IAI has expanded its UAV activity, which is one of its main fields, and has made the company one of the world's leaders in this technology.

Because of cost considerations, the move is for future fighter aircraft to be multi-role. The U.S. JSF will enter service with the U.S. Air Force, Navy, and Marines and the British Royal Navy. Russia, for the first time, will develop multifunctional aircraft and is retrofitting older aircraft (e.g., MiG-29 to MiG-29SMT) for multiple roles.

Asia remains a market, not a maker, of truly advanced military aircraft. Those countries with their own aviation-manufacturing industries are mainly producing American or Russian versions under license. China, which has the largest research and development (R&D) program, is building several new fighters, but many are derived from Western designs. These are modern aircraft, though not on the cutting edge. When the planes enter service after 2000, China will have mainly replaced its huge numbers of 1950's-era aircraft with 1980's models.

Country	Aerodynamics	Aeronautical Propulsion	Aeronautical Structures	Aeronautical Vehicle Control	Aeronautical Subsystems and Components	Aeronautical Design and Integration
Australia		●	●			
Brazil	●					
Canada	●●●	●	●	●	●●	●
China	●	●	●●		●	●
France	●●●	●●●	●●●	●●	●●●	●●
Germany	●●●	●●●	●●●	●●●	●●●●	●●
India	●	●				
Israel	●	●	●	●	●●	●
Italy			●	●		
Japan	●	●●●	●●●	●●	●●●	●●
Netherlands			●	●	●	
Russia	●●●	●●●●	●●●	●●●	●●	●●
South Korea					●	
Spain	●					
Sweden	●●	●●	●●		●●	
Switzerland	●	●	●		●●	
UK	●●●	●●●●	●●●	●●●	●●●	●●●
United States	●●●●	●●●●	●●●●	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 1.0-2. Aeronautics Technology WTA Summary

SECTION 1.1—AERODYNAMICS

Highlights

- Tailless fighters can reduce weight, drag, and radar signature and increase range, maneuverability, and survivability.
- The Canard Rotor Wing (CRW) concept combines the low-speed flight characteristics of a helicopter with high-speed, fixed-wing capabilities.
- Concepts being evaluated for mid-size jet transport aircraft include conventional, high-wing aircraft, BWB aircraft, and box-wing aircraft with multiple refueling booms.
- Improved design methodologies and analysis tools are essential in reducing costs and enhancing vehicle capability in the future.

OVERVIEW

This section includes those technologies that relate to designs or innovations that improve the aerodynamic characteristics of surfaces or bodies, with the goal of obtaining better flow patterns (subsonic and supersonic) and achieving improved lift and drag parameters. The technologies may apply to air vehicle external surfaces and to internal flow streams, such as those contained within propulsion units or other devices. The technologies also include flow control and the application of computational fluid dynamics (CFD) to achieve accurate flow prediction for design optimization.

Tailless fighters are being pursued as a means to improve agility and stealth characteristics. NASA and Boeing Co. produced the X-36 (see Figure 1.1-1), a 28-percent scale prototype that lacks horizontal and vertical tails and uses split-aileron and engine thrust vectoring for flight control. The design promises a decrease in weight, drag, and radar signature and an increase in range, maneuverability, and survivability for future fighter aircraft.

Figure 1.1-1. X-36 Over the Mojave Desert

In response to a Navy requirement for an unmanned, high-speed, ship-based, vertical take off and landing (VTOL) vehicle, McDonnell Douglas Helicopter (now Boeing Company) developed a concept called CRW (see Figure 1.1-2). The CRW would spin a center wing to take off like a helicopter. The vehicle would accelerate to about 120 kn, when flaps would deploy from the front and rear wings. Flap deployment would offload the spinning center wing, which would stop rotation and be locked into a position across the fuselage to perform as a third wing. The flaps on the other two wings would then be retracted, and all three wings would provide the lift loads for fixed-wing flight. A reverse of these events would transition the CRW back to its rotary wing/VTOL mode for landing on small landing areas.

Figure 1.1-2. CRW Aircraft

A configuration where the wing and fuselage are blended together (see Figure 1.1-3) into one structural component is attractive for future tanker/transport aircraft. The BWB configuration provides generous internal volume for fuel and cargo and reduced structural weight. The concept can employ multipoint refueling and, by the nature of its basic shape, has low observable (LO) characteristics.

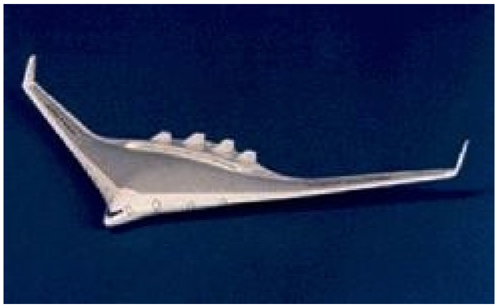

Figure 1.1-3. BWB Aircraft

Joined wing (or box wing) aircraft (see Figure 1.1-4) are being considered for several types of aircraft. Lockheed Martin Aeronautical Systems has studied a joined-wing aircraft as a tanker with two refueling booms to increase the number of stations available for refueling aircraft. Smaller joined wing aircraft could embed advanced sensors in the wing to support aircraft operation and mission needs.

Figure 1.1-4. Joined-Wing Aircraft

Advanced CFD analysis capabilities are critical to the design of advanced aircraft. For example, improved CFD-based (Navier-Stokes) design methodologies and analysis tools enable cost reduction and operational enhancements.

RATIONALE

Aerodynamics is the underlying science of all aeronautic systems. Advances in the science, as applied to transportation, have taken mankind from a sail on a ship to the supersonic transports and fighter aircraft of the 21st century. While the large, rapid leaps in air-vehicle performance of the 20th century may not be available in the near future, affordable, relevant improvements are ongoing.

The ability to control airflow through any means while in flight results in increased maneuvering capability and survivability enhancement.

Global-range aircraft will enable worldwide response to crises in a minimum amount of time. Joined-wing or BWB tankers can provide the same number of refueling booms on half as many aircraft. This is especially important because budget economics dictates that current aircraft will not be replaced on a one-for-one basis.

Preliminary analyses indicate that the BWB would outperform all conventional large aircraft. An initial evaluation of this configuration indicated significant cost and performance benefits over conventional configurations: a 56-percent increase in lift/drag (L/D) ratio, a 20-percent decrease in fuel burn, and a 10-percent decrease in the operating-empty weight. The cargo aircraft, with a 280-ft wingspan, could carry 231,000 lb of payload more than 7,000 nmi at a cruise speed of approximately 560 mph. This is almost twice the capacity of the Boeing 747-400. It would reduce fuel burn and harmful emissions per passenger mile by almost a third in comparison to today's aircraft. Other potential benefits of the BWB include lower operating cost and reduced community noise levels.

WORLDWIDE TECHNOLOGY ASSESSMENT (see Figure 1.1-5)

Aerospatiale, British Aerospace (who built the Concorde), and Daimler-Chrysler Aerospace have already pooled their preliminary projects in the European Supersonic Research Programme (ESRP). Their objective is to deliver by the year 2010 a new-generation supersonic aircraft (see Figure 1.1-6) that will carry up to 300 passengers, at an altitude of over 10,000 km and at a cruising speed of Mach 2.2. This aircraft would have half the Concorde's fuel consumption per passenger. Market projections estimate a need for at least 500 of these aircraft between 2007 and 2025.

Airbus is planning to develop the A3XX (see Figure 1.1-7), a long-range, double-decker jumbo jet that could seat between 500 and 600 passengers.

Country	Advanced Wing Planforms	Airflow Control
Brazil		●
Canada	●	●●●
China	●	●
France	●●●	●●●
Germany	●●●	●●●
India		●
Israel	●	●
Japan		●●
Netherlands	●	●
Russia	●●●	●●
Spain		●
Sweden	●	●●
Switzerland		●
UK	●●●	●●●
United States	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 1.1-5. Aerodynamics Technology WTA Summary

Figure 1.1-6. Second-Generation Supersonic Transport

Figure 1.1-7. Airbus A3XX

LIST OF TECHNOLOGY DATA SHEETS
III-1.1. AERODYNAMICS

DATA SHEET III-1.1. BLENDED WING/BODY (BWB)

Developing Critical Technology Parameter	Compared with current aircraft of similar size: • Greater than 50-percent increase in L/D ratio • 25-percent decrease in fuel consumption • 10-percent decrease in operating weight • 15-percent decrease in direct operating costs
Critical Materials	Low-cost composites.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Advanced control algorithms, such as neural nets, to support flight controls.
Technical Issues	Systems integration (airframe/engine); safety; logistics. Commercial: landing length and logistics at airports; Federal Aviation Administration (FAA) time limits to deplane passengers in an emergency; advanced flight controls. Military: advanced flight controls; short takeoff and landing.
Major Commercial Applications	BWB is being developed for commercial use.
Affordability	Would reduce direct operating costs compared with conventional wide-body aircraft using equivalent technology.

RATIONALE

Although efforts have been aimed at developing a commercial BWB aircraft, there is significant military potential in such a planform. A BWB offers potential fuel, noise, and cost benefits. A flying-wing design offers more potential for wing laminar flow applications. The major hindrance to developing very large transports with BWB may be safety considerations in the event of a crash or the number of passengers that could be lost in a crash.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●	France	●●●	Germany	●●●
Russia	●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Experience gained from the development of the B-2 gives the United States a distinct advantage in the design and development of BWB aircraft. It would be too risky for a country to develop without investing in a large-scale prototype. A wide-ranging BWB design study is underway at the College of Aeronautics at Cranfield University in the United Kingdom. An international effort—a BWB, UHCA/VLCT—involves Aerospatiale (France) and Daimler-Benz (Germany).

BACKGROUND

Efforts are underway to study large BWB aircraft that would carry 800 passengers. Initial team members studying the BWB concept were Boeing (McDonnell Douglas), Stanford University, the University of Southern California, Clark Atlanta University, the University of Florida, and NASA's Langley and Lewis Research Centers.

behind this design approach is to maximize overall efficiency by integrating the engines, wings, and the body into a single lifting surface. The BWB concept houses a wide double-deck passenger compartment that actually blends into the wing. Adjacent to the passenger section is ample room for baggage and cargo.

Preliminary analyses indicate that the BWB would outperform all conventional large aircraft. It is conceived to carry 800 passengers (almost twice the passenger capacity of the Boeing 747-400) over 7,000 miles at a cruise speed of approximately 560 mph. It would reduce fuel burn and harmful emissions per passenger mile by almost a third in comparison to today's aircraft. Other potential benefits of the BWB include lower operating costs and reduced community noise levels.

In August 1999, NASA announced that the BWB would be one of three advanced aeronautical concepts as quick starts in its Revolutionary Concepts (REVCON) project, which encourages the development of ideas that could lead to revolutionary new aircraft.

DATA SHEET III-1.1. BOX WING

Developing Critical Technology Parameter	A 20-percent reduction in ramp space. Acquisition and operating cost improvements exceeding 20 percent over current transport aircraft.
Critical Materials	Low-cost metallic structures.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Equivalent laminated plate solution (ELAPS) (based on Ritz function principle).
Technical Issues	Wing-section design to minimize interference between forward and aft wings; wing end-plate structure (requires high stiffness and high fatigue strength); aeroelastic interaction of connected wing system.
Major Commercial Applications	Commercial airliners.
Affordability	Saves on ramp space.

RATIONALE

NASA is the lead agency for the development of this planform for large transport aircraft. Major military use would be in a tanker configuration. Dual-boom capability can occur while retaining the roll-on, roll-off capability of vehicles, cargo, and International Standards Organization (ISO) containers. These aircraft are intended to fill the vacuum that will be created by the retirement of the C-141s and serve as the projected replacements for the KC-135. They would have the flexibility to meet most of the needs of the military as cargo and personnel carriers and tankers in regional conflicts, peacekeeping endeavors, and humanitarian projects.

The box-wing planform can be applied to both large and small aircraft. Figure 1.1-8 represents a 325-passenger version. Large box-wing aircraft (600+ passengers) could operate within existing international airports, and no infrastructure changes would be necessary. Five box-wing aircraft could be parked in the gate space of four conventional aircraft designed for the same payload, allowing airlines to avoid a billion-dollar investment in a new terminal to add gates. This would also benefit the military as it deploys worldwide.

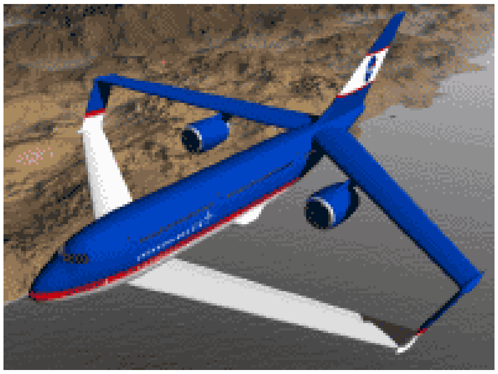

Figure 1.1-8. Lockheed-Martin/ NASA Box Wing Airliner

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●●	Germany	●●●	Russia	●●●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

No box-wing aircraft is currently in production anywhere. However, the technology is well understood, and most countries with some aircraft capability could produce a subsonic version of such a planform.

DATA SHEET III-1.1. HIGH ASPECT RATIO, STRUT-BRACED WING

Developing Critical Technology Parameter	Structurally sound wings for large aircraft with an aspect ratio greater than 12.
Critical Materials	Low-cost metallic structure; low-cost composite structure; integrally stiffened fuselage panels.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Flight control algorithms.
Technical Issues	Wing/strut system optimization—wing and strut aerodynamic design to minimize interference between the wing and strut while minimizing the overall wing/strut structural weight; aeroelastic interaction of wing/strut system.
Major Commercial Applications	Large passenger transports. The high aspect ratio, strut-braced wing configuration is applicable to a wide range of civil aircraft. The increased aerodynamic efficiency will greatly reduce fuel consumption and the aircraft size for a given payload/range requirement.
Affordability	NASA-sponsored studies of high aspect ratio, strut-braced wing transport aircraft indicate an acquisition and operating cost improvement of 8–10 percent over current transport aircraft. Lockheed-Martin studies showed a 23–26 percent reduction in direct operating costs and 21–23 percent reduction in acquisition costs.

RATIONALE

A high aspect ratio, strut-braced wing could be built with no new technology breakthroughs, but advanced materials technology would make the concept more affordable. The strut-braced wing transport concept (see Figure 1.1-9) greatly reduces subsonic transport weight while improving aerodynamic performance. The result is a transport aircraft that has greatly reduced size, acquisition cost, and operating costs. For military use, the high wing configuration is very similar to existing military cargo aircraft (C-141, C-5, C-117) and can incorporate the loading and airdrop features of those aircraft, including roll-on/roll-off loading of vehicles, equipment, and ISO containers.

Figure 1.1-9. Lockheed-Martin/ NASA High Aspect Ratio, Strut-Braced Wing Airliner

The strut-based configuration also supports a multipoint aerial refueling system by locating the booms and/or drogues at the wing/strut interface on each wing. It would provide the operational advantage of multipoint/ multi-boom refueling with advanced aerodynamics and reduced operating costs. The strut-braced wing tanker can be configured to refuel one receptacle and one probe-equipped aircraft nearly simultaneously (multi-Service, multinational capability). Joint Vision 2010 states that “power projection . . . will likely remain the fundamental strategic concept of our future force.” Rapid strategic mobility enhanced by strut-braced transport aircraft could be an important part of that concept

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●	France	●●●	Germany	●●●
Netherlands	●●●	Russia	●●●	UK	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

NASA conducted studies of high aspect ratio, strut-braced winged aircraft in the early 1980s. Virginia Polytechnic Institute and State University began studies of the strut-braced wing concept in 1996. U.S. Government-sponsored contractor work began in 1998. No high aspect ratio, strut-braced wing, jet-powered transport aircraft is currently in production anywhere in the world.

DATA SHEET III-1.1. TAILLESS

Developing Critical Technology Parameter	Aircraft overall and side sector radar cross section (RCS) signature reduction of 15 percent. Subsonic and supersonic cruise drag reductions of 15 percent.
Critical Materials	Low-cost, high-temperature materials for vectoring nozzle applications.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Vehicle control algorithm.
Technical Issues	Integration of other technologies (i.e., vehicle control, thrust vectoring).
Major Commercial Applications	None identified.
Affordability	Tailless aircraft reduce nonrecurring costs in several ways. Eliminating the tail is a direct cost, weight, and drag savings. These savings enable further decreases since the aircraft can be made smaller and less expensive. The drag and weight reductions provide further operational savings in the form of reduced fuel usage.

RATIONALE

Tailless military aircraft have the potential to reduce greatly overall RCS values, particularly in the side sector. The prime technologies associated with tailless designs (excluding specific signature-reduction features) include control effectors and flight control/vehicle management system design. To provide levels of maneuverability and agility comparable to conventional designs typically requires that a tailless aircraft has a more complex suite of control effectors. The application of tailless planform to other aircraft (e.g., B-2) is well proven.

The key technical issue for tailless aircraft is proving the feasibility for a flight control system (FCS) capable of controlling a highly directionally unstable aircraft. A measure of instability is the time to double amplitude (TDA). Tailless fighter designs have TDAs of 0.2 sec. This means that the flight control will have to detect and correct for any disturbance in less than that amount of time.

A tailless planform could provide an advanced fighter with good maneuverability and agility. Tailless aircraft have less drag and weight and fewer actuators and flight control surfaces. This would increase range. One of the motivations for tailless aircraft is associated with reducing RCS. Another use is in UCAVs. Boeing's entry in the UCAV Advanced Concept Technology Demonstration (ACTD) is a tailless, 27-ft long aircraft that has a 34-ft wing and weighs 8,000 pounds.

This technology is ready for application to advanced military vehicles.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Germany	●●●	Israel	●●	Russia	●●●
Sweden	●●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The Boeing Company and NASA teamed to develop a prototype fighter aircraft designed for stealth and agility. The result was a subscale tailless aircraft called the X-36 (see Figure 1.1-10). Germany has had a long history of work with tailless aircraft dating to the mid 1930s. In France, a flying wing was patented in 1929. In the United Kingdom, a Tailless Aircraft Advisory Committee was established in 1943 to research what was perceived to be the most promising layout for fast aircraft/tailless aircraft. Although the capability exists, no tailless aircraft fighters have been developed.

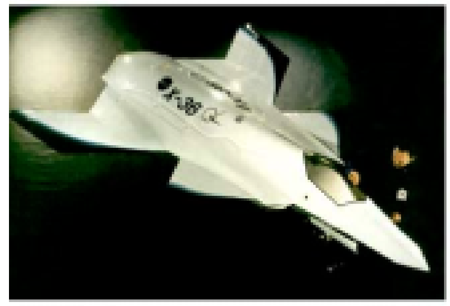

Figure 1.1-10. X-36 Aircraft

BACKGROUND

Tailless aircraft are not a new concept. It has been pursued throughout the 1900s by a variety of designers. Flying wings (e.g., the XB-49) have been tailless. Sport planes have been flown tailless. The concept is now being evaluated for future, high-performance aircraft.

The NASA/Boeing partnership project, the X-36, is a tailless 28-percent scale, experimental aircraft that will dramatically change the design of future stealth fighters. The remotely piloted X-36 has no vertical or horizontal tails, yet it is expected to be more maneuverable and agile than today's fighters. Its revolutionary design was built at a fraction of the cost and schedule typical of other X-aircraft. The tailless design reduces the weight, drag, and RCS typically associated with traditional fighter aircraft. It incorporates new flight control technologies in place of vertical and horizontal tails to improve the maneuverability and survivability of future fighter aircraft. During flight, the X-36 uses new split ailerons and a thrust vectoring nozzle for directional control. The ailerons not only split to provide yaw (left and right) control but also raise and lower asymmetrically to provide roll control. The X-36 vehicle also incorporates an advanced, single-channel digital fly-by-wire control system developed with commercially available components. The X-36 first flew in the summer of 1997 and completed its flight test schedule in November of that same year. For links to web sites with information on tailless aircraft, go to Internet address http://www.halcyon.com/bsquared/winglinks.html.

DATA SHEET III-1.1. FLOW CONTROL EMPLOYING MICROELECTROMECHANICAL SYSTEMS (MEMS)

Developing Critical Technology Parameter	Reducing drag by up to 50 percent.
Critical Materials	Silicon wafers and other materials used in the micro-electronics fabrication industry.
Unique Test, Production, Inspection Equipment	Particle-Imaging Velocimetry (PIV) flow measurement; MEMS fabrication techniques. Production facilities to fabricate and package large arrays of MEMS devices.
Unique Software	Laminar flow control validation.
Technical Issues	Use of MEMS for flow control requires significant research into fundamental flow physics, control algorithm development, communication, and MEMS fabrication. Small-scale demonstration is 5+ years in the future. Micro actuation strategies used to achieve desired aerodynamic functionality (e.g., maximum L/D, minimum inlet flow distortion) in fixed-geometry flowpaths. Ability to integrate MEMS devices successfully into aircraft structure, survivability of MEMS devices in harsh military environments, ability of MEMS devices to provide adequate control at high speeds.
Major Commercial Applications	Potential in all commercial aircraft for increasing range, payload, and reducing life-cycle cost; specifically, ice-buildup warning sensors, wing laminar flow control and flow separation control, high lift, inlet flow control.
Affordability	Fabrication and packaging of MEMS arrays could significantly affect affordability.

RATIONALE

Active flow control can reduce aircraft friction drag and control separation on wings and inlets. Increased range resulting from decreased drag will contribute to the power projection envisioned in Joint Vision 2010. Reduced takeoff and landing distances will enable aircraft to operate out of smaller fields.

Existing flow control systems using conventional air injection or mechanical actuation typically have significant impacts on weight, signature, and cost. MEMS technology has the potential to minimize these adverse impacts while maintaining a significant level of control effectiveness. Agility of aircraft with reduced RCS signature can be greatly enhanced. The most significant issue is the development of reliable, maintainable, and survivable MEMS effector and sensor arrays for military environments.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●	France	●●●	Germany	●●●
India	●	Japan	●●●	Netherlands	●●	Norway	●●
South Korea	●●	Sweden	●●	Switzerland	●●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States, the Department of Defense (DoD) and industry are developing this technology. France, Germany, Japan, and the United Kingdom are also active in this technology area. Programs of lesser impact are in place in Canada, China, India, Netherlands, Norway, South Korea, Sweden, and Switzerland. More information on defense applications can be found at http://www.ida.org/mems and in *Militarily Critical Technologies, Part III: Developing Critical Technologies, Section 12: Manufacturing and Fabrication Technology*.

DATA SHEET III-1.1. FOREBODY VORTEX FLOW CONTROL

Developing Critical Technology Parameter	Increase maneuverability by 15 percent and increase nose pointing ability by 25 percent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Air supply and control valves.
Major Commercial Applications	None identified.
Affordability	Cost of air supply and control valves for pneumatic systems may have a negative impact on affordability.

RATIONALE

Forebody vortex flow control provides a means to generate yaw and roll moments for high-performance aircraft at moderate-to-high angles of attack. This allows increased agility to be achieved. The increased nose-pointing ability will give fighters an advantage during aerial engagements. Both mechanical and pneumatic methods have been investigated. Applications to date have focused almost exclusively on low-speed flight conditions. With the advent of reliable and effective thrust vectoring systems, the emphasis on forebody vortex control technology has diminished. Future efforts in this area may prove fruitful if designers can develop simple flow control systems that will modify not only the forebody vortex pattern but will also provide aerodynamic benefits in other parts of the flight envelope. The key reason this technology has not been applied so far is that it is too unconventional for designers to embrace.

Forebody vortex flow control has been successfully demonstrated on the X-29. The only remaining hurdle is development of a fully integrated system, especially one that integrates the forebody vortex control system with the radar in the aircraft nose. Another area of interest is for high fineness ratio missiles, with the goal of eliminating fins and strakes.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●	France	●●●	Germany	●●●
Russia	●●●	Switzerland	●●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Currently, active application of this technology seems to generate little interest. Passive means to control forebody vortices (mainly for stabilization of the vortex pattern) have been seen on aircraft from several European nations including Switzerland (modified Mirage) and Russia (MiG-29). The principles are understood well enough so that an active forebody vortex control system could be developed by most nations with the capability to design high-performance fighter aircraft.

DATA SHEET III-1.1. LAMINAR FLOW CONTROL (LFC)

Developing Critical Technology Parameter	Reducing drag by up to 50 percent.
Critical Materials	Smart materials, such as shape memory alloys; flexible materials technologies.
Unique Test, Production, Inspection Equipment	Unique wind-tunnel test and measurement facilities, such as the Unsteady Low-Speed Wind Tunnel at Arizona State University.
Unique Software	Advanced CFD methodologies; boundary layer stability analysis codes.
Technical Issues	Fundamental understanding of the physics of turbulent transition; manufacture of LO-compatible MEMS and smart structures.
Major Commercial Applications	Can be used for both military and commercial applications. Military application is more difficult because of observables requirements. Minimize flow separation to maximize lift and L/D ratio.
Affordability	Cost of air supply and control valves for pneumatic systems may have a negative impact on affordability.

RATIONALE

As air moves over an airfoil, it travels in two distinct modes. From the leading edge of the airfoil the molecules travel in an orderly, nearly parallel stream in layers. The flow in this area is called "laminar" and hugs the airfoil. The flow continues to separate at some point that is defined by numerous parameters, such as shape, surface roughness, angle of attack, and so forth. It then transitions to a turbulent area characterized by random movement, vortices, and high drag. The lift is created in this laminar flow area. Thus, control of the flow and separation point greatly contribute to the lift and L/D ratio.

LFC offers revolutionary capability to increase range and loiter of both military and commercial aircraft. Hybrid LFC can reduce minimum drag by as much as 50 percent and increase range by as much as 30 percent on flying wing-type aircraft designs. LFC can also significantly reduce the skin temperature of supersonic and hypersonic aircraft, allowing larger portions to be manufactured using aluminum instead of titanium. LFC can improve maximum lift and maneuver L/D. LFC can also minimize flow separation and control vortical structures to improve maneuverability and survivability. Supersonic laminar flow offers revolutionary capability to decrease the weight and cost of supersonic cruise aircraft.

Control of vortices and flow separation can reduce cruise drag and increase maneuver L/D. This enhances the survivability and maneuverability that would support the operational concept of dominant maneuver found in Joint Vision 2010. The development of active flow control technologies using conventional actuators has the potential to provide significant aerodynamic performance gains. Successful demonstration of technology is primarily dependent on understanding the flow physics of the application and proper implementation of control algorithms rather than development of the flow control effectors. System-level integration of conventional actuation methods may adversely affect weight and cost. The effectiveness of such a system must be demonstrated over a useful range of varying operating conditions.

WORLDWIDE TECHNOLOGY ASSESSMENT

Brazil	●●	Canada	●●●	China	●	France	●●●
Germany	●●●	Israel	●●	Japan	●●	Russia	●●●
Spain	●●	Sweden	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Most foreign nations with the capability to design and produce modern combat aircraft have shown interest in flow control technology. Many integration issues remain in producing a practical military aircraft with laminar flow. Standard wing suction and blowing techniques are possible in the near term, but application of MEMS to reduce laminar flow is still only in the basic research phase.

DATA SHEET III-1.1. VISCOUS DRAG REDUCTION

Developing Critical Technology Parameter	Reduce turbulent skin friction drag by 12 percent using passive means; by 20 percent using active means. Passive approaches include riblets, films, and other surface features. Active approaches include MEMS-based actuators and sensors with distributed processing for control.
Critical Materials	Smart materials, such as shape memory alloys; flexible materials; adhesive films.
Unique Test, Production, Inspection Equipment	High resolution, rapid frame optical diagnostic techniques, such as PIV; unique wind tunnel test and measurement facilities such as the Unsteady Low-Speed Wind Tunnel at Arizona State University.
Unique Software	Advanced CFD; control software for active approaches.
Technical Issues	Manufacturing LO-compatible MEMS and smart structures; developing active systems at acceptable cost, weight, durability, and maintainability.
Major Commercial Applications	All large aircraft; ground transportation (e.g., buses, trains).
Affordability	Passive coatings cost must be compared with the cost of painting and periodic paint removal. Increased range and reduced fuel consumption could justify the expense of manufacturing riblets.

RATIONALE

Viscous drag reduction offers revolutionary capability to increase range and loiter of both military and commercial aircraft. Viscous drag reduction technologies have the potential to extend air vehicle range and reduce fuel consumption. Passive approaches have been demonstrated to reduce skin friction drag by 6–12 percent, giving total vehicle drag reduction of 3–6 percent. Active approaches demonstrated numerically and in the laboratory appear to reduce skin friction drag 10–25 percent, giving a vehicle drag reduction of 5–12 percent.

Drag reduction translates directly into increased vehicle range. Further development of active approaches is needed. Advanced diagnostic and simulation tools are required for this development, including PIV and direct numerical simulation. Adhesive film technology is critical for cost-effective implementation and retrofit of existing aircraft with this technology. Active approaches may be too costly, heavy, and/or difficult to maintain to be practical. Passive techniques could replace paint with adhesive film, reducing cost and environmental problems.

Strategic mobility is key to providing the United States with future power projection capability and is enabling the concepts espoused in Joint Vision 2010.

WORLDWIDE TECHNOLOGY ASSESSMENT

Brazil	●●	Canada	●●●	China	●	France	●●●
Germany	●●●	India	●●	Israel	●●	Japan	●●
Russia	●●●	Spain	●●	Sweden	●●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Passive devices have been studied for close to 20 years. Much of the passive technology has been published in the open literature, and patents have been granted for much of the passive and active technology. Airbus and

European researchers are familiar with the technology. Airbus is probably closest to applying viscous drag reduction to a commercial aircraft. They have shown more interest than military and other commercial users.

In India, the National Aerospace Laboratories initiated an active program to assess viscous drag reduction and understand aspects of flow structure on typical aircraft components for low and transonic speeds. India is using riblets and are applying lessons learned to commercial ground transportation (e.g., buses, trains). Riblets with symmetric v-grooves manufactured by 3-M company (United States) have been widely used in their research. Drag reduction was as high as 15 percent at an incidence of 6 deg on a National Advisory Committee on Aeronautics (NACA) 0012 airfoil at low airspeed.

BACKGROUND

Viscous drag can amount to 40–50 percent of the total drag, so any decrease can lead to substantially reduced fuel expenditures. This fuel saving can translate directly into millions of dollars of reduced operating costs for the industry.

DATA SHEET III-1.1. VISCOUS FLOW CONTROL

Developing Critical Technology Parameter	A 15-percent improvement of L/D at high angles of attack.
Critical Materials	Smart materials, such as shape memory alloys; flexible materials.
Unique Test, Production, Inspection Equipment	Wind tunnel test and measurement facilities, such as the Unsteady Low-Speed Wind Tunnel at Arizona State University; high resolution, rapid-frame, optical diagnostic techniques, such as PIV.
Unique Software	Boundary layer stability codes and active flow control models embedded in advanced CFD analysis and design codes.
Technical Issues	Actuators including pulsed microjets, on-demand vortex generators, and microbubbles; compatibility with LO technologies.
Major Commercial Applications	Improvement of landing margins for commercial aircraft. Improvement in the efficiency of control surfaces would allow reduction in control surface size.
Affordability	Cost could be lower because it would be less complex than bleed systems. Cost benefit could be achieved by reducing aircraft weight and eliminating or reducing control surface size.

RATIONALE

System-level performance is greatly diminished in the presence f separated flow. Flow separation occurs at some operating condition for most internal (e.g., inlets) and external (e.g., airfoils) flow environments. Micro-vortex generators are a low-cost technology that provides significant flow separation control by re-energizing the flow before separation. The reattached flow reduces overall drag and wake spread to increase overall performance.

The primary objective is to control flow separation caused by curvature, adverse pressure gradients, or shock-wave boundary-layer interactions. Viscous flow control would reduce stall, improve control surface effectiveness, improve L/D for high-angle-of-attack flight, improve inlet performance for highly curved inlet ducts or supersonic conditions, and improve maneuverability. A wide variety of approaches are available to achieve viscous flow control, including steady and pulsed microjets, synthetic jets, on-demand vortex generators and elastic microbubbles for vortex generation, and boundary-layer bleed and wall jets for boundary layer profile manipulation.

Viscous flow control could be used to control separation (improving propulsion system performance, particularly at maneuver speeds), improve performance of high-speed inlets, delay stall, and improve control surface effectiveness. Current research to control separation with small-scale, non-intrusive actuators shows promise. Actuators could be used on demand, possibly in off-design conditions, and their effects would be eliminated at cruise, giving drag reduction that compares with passive separation control devices. Active approaches would allow tailoring of flow field by adjusting actuator output to local flow conditions based on MEMS or other sensors. This would provide an optimal control scheme over a wide range of flow conditions.

Viscous flow control methods are in a range of maturities. Vortex generators and boundary-layer bleed are in use. Steady microjet vortex gererators are ready for application. Synthetic jets, pulsed microbubbles, and on-demand vortex generators require additional development. Advanced flow diagnostic methods will help to accelerate the development of this technology.

WORLDWIDE TECHNOLOGY ASSESSMENT

Brazil	●●	Canada	●●	China	●	France	●●●
Germany	●●●	Israel	●●	Japan	●●	Russia	●●●
Spain	●●	Sweden	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

All aircraft manufacturers are likely to be studying this technology. The advanced actuation approaches are not as widely studied, and developer tend to maintain proprietary and/or patent rights over their developments. The open literature provides access to many of the recent developments, although many of these publications probably provide outdated information.

SECTION 1.2—AERONAUTICAL PROPULSION

Highlights

- Enhanced technologies in turbine engines will result in increased range and payload at lower cost.
- Low cost will be realized by having common core (engine) architecture, ease-of-assembly design, and health monitoring systems.
- Thrust vectoring nozzles will reduce the weight, maintenance, and cost of aircraft and will improve maneuverability.
- Developments in ramjet/scramjet technology may enable hypersonic aircraft to be realized in an economical manner.

OVERVIEW

This section covers the propulsion systems and fuels that power all types of air vehicles. Air vehicles include, but are not limited to, fixed-wing aircraft, rotary-wing aircraft, hybrids such as tilt-wing aircraft, and UAVs. The category of UAVs also includes missiles that have their operational envelope within that portion of the atmosphere that can support air-breathing propulsion systems.

The type of propulsion system most prevalent in military air vehicles today is the gas turbine. This section covers gas turbines, along with other engines such as the ramjet, scramjet, and pulse-detonation engine (PDE). The engines may be at any scale—from that of the large transport aircraft down to the MAV. Also included, where appropriate, are components of power trains associated with the transmission of power from the power plant to the point of application to the air. This includes power conversion devices, such as gearboxes and transmissions.

The United States has a national program to double the U.S. military's 1988 propulsion capacity: the Integrated High Performance Turbine Engine Technology (IHPTET) program. IHPTET set very aggressive goals for the year 2003: to provide durable performance with low production and maintenance costs for new fighters and upgrade potential for currently fielded systems. Specific performance and cost goals are being considered to the year 2015 and beyond. Development of advanced materials is a critical part of this effort. Increased temperature and strength organic matrix composites, ceramic matrix composites, super alloys, and intermetallic composites are key to increasing engine thrust-to-weight ratio. Reducing fuel consumption through higher component efficiencies and compression system pressure ratios is an important aspect of future turbine engines. Future turbine engines will have very low fuel consumption, high thrust-to-weight ratio, and low cost in all phases of their life cycles. Compared with 1988 technologies, turbine engines in the period 2009–2015 will have 2.5–3.0 better thrust-to-weight ratio, 20- to 30-percent better specific fuel consumption, and 50-percent reduction in total development, production, and maintenance costs.

Other forms of propulsion are also being investigated. The scramjet engine is the key enabling technology for NASA's multi-year hypersonic flight research program, Hyper-X, which seeks to overcome one of the greatest aeronautical research challenges: sustained air-breathing hypersonic flight. The Air Force Wright Patterson Laboratories, in collaboration with Johns Hopkins University/Applied Physics Laboratory (JHU/APL), are developing storable fuel scramjet engine technology under the Hydrocarbon Scramjet Engine Technology (HySET) program.

Ramjets operate by subsonic combustion of fuel in a stream of air compressed by the forward speed of the aircraft inlet as opposed to conventional turbojet engines, in which the compressor section (the fan blades) compresses the air. In comparison to turbojets, ramjets have no moving parts exposed to the engine airflow.

Scramjets (supersonic-combustion ramjets) are ramjet engines in which the airflow through the whole engine remains supersonic. Testing scramjet engine technology is challenging because only limited duration (i.e., 1–3 min) testing can be performed in ground facilities because of the extremely high-energy requirements. Long duration, full-scale testing requires flight tests above Mach 5. Hyper-X (X-43) (see Figure 1.2-1) will build knowledge, confidence, and a technology bridge to Mach 10. The fuel for the X-43 will be gaseous hydrogen.

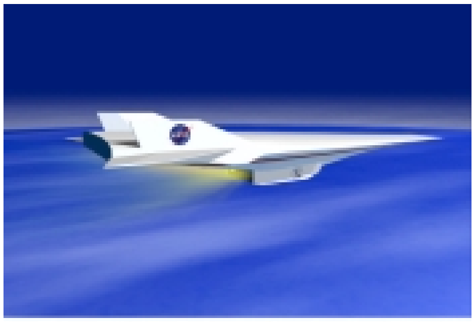

Figure 1.2-1. X-43, Hyper-X (With Scramjet Firing)

Rockets carry their own oxygen (liquid) for combustion. An air-breathing scramjet engine burns oxygen scooped from the atmosphere in the same manner as normal jet engines. Using conventional turbojet technology, air-breathing hypersonic vehicles should carry more cargo/payload than equivalent rocket-powered systems since they have more weight and payload space available because of not having to carry oxidizer onboard.

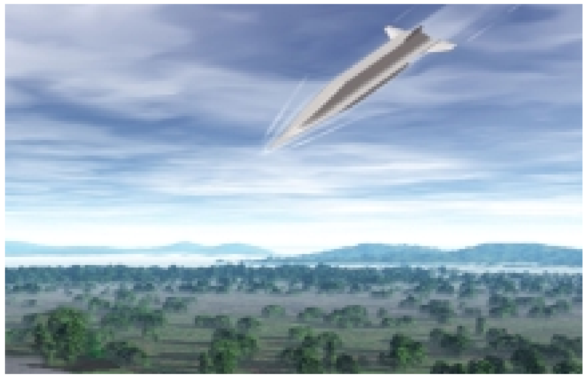

Figure 1.2-2. Storable Fuel Scramjet Strike Missile

Military applications of scramjet technology include long-range reconnaissance and rapid strike missions (see Figure 1.2-2). Operation at hypersonic velocities allows Continental United States (CONUS)-based surveillance missions within hours of request and multiple passes without the predictability of satellite orbits. High speed and altitude supplant expensive stealth technology to achieve survivability for hypersonic vehicles and cruise missiles.

One of the propulsion advances that will be put in future aircraft are thrust vectoring engines. These engines have flown in aircraft since the 1970s and are currently used in the F-15 Advanced Control Technologies for Integrated Vehicles (ACTIVE) and the X-36. They are expected to be used in fighters, UCAVs, BWB aircraft, and commercial aircraft.

RATIONALE

Propulsion sources for military vehicles—as opposed to civilian use engines—must provide superior performance because of the rigorous demands placed upon them. Increases in power-to-weight ratios, maximum power output, fuel efficiencies, and durability are characteristics sought after in civilian and military applications. However, the military propulsion unit must have additional characteristics that are superior to those of adversaries. Rapid and violent cycle changes, operation in severe climatic conditions, and the hardening to withstand nuclear and electromagnetic shocks are some of the distinguishing differences between the two applications.

Advanced technologies will be critical in providing military capability within budget limitations. Improved propulsion will allow global reach transports that have 50 percent greater range than the C-5 transport and 40 percent greater payload, will double the range of the B-1 bomber in half the time at 30 percent lower cost, will provide aircraft carrier support aircraft that have twice the time on station, and will enable supersonic VTOL fighters with twice the range and payload of the F-15 and UAVs that have twice the loiter capability and 3.5 times the range of the E-2. Low cost will be realized by reducing or eliminating the need for lubrication, hydraulics, and other subsystems while employing common core (engine) architecture, ease-of-assembly design, and health monitoring systems.

Improvements in the control of fuel components and mix ratios will result in better efficiencies and reduced emissions to reduce vulnerability to signature-seeking weapons.

Current after-burning exhaust systems are heavy and costly because of system complexity. Thrust vectoring nozzles will reduce the weight, maintenance, and cost of the aircraft and will improve maneuverability.

For helicopters, propulsion, drive-train, and power-transfer research is required to reduce specific fuel consumption, increase horsepower-to-weight ratio, and lower the cost, volume, and noise of future and current systems.

WORLDWIDE TECHNOLOGY ASSESSMENT (see Figure 1.2-3)

Japan's National Aerospace Laboratory (NAL) has completed a series of studies on the overall performance of aircraft propulsion systems, internal fluid dynamics, advanced fans and compressors, advanced combustor design, high-efficiency turbines, control system and instrumentation for advanced engines, materials and structures for engine components, measurement methods for gas turbine aircraft propulsion systems, ultrahigh bypass engine, turbo-air breathing engines for space plane, ceramic gas turbine, super/hypersonic transport propulsion systems, and contra-rotating turbomachines.

The United Kingdom has strong capabilities in high-performance power-transmission technologies. The Defence Evaluation and Research Agency (DERA) has the experimental capability required to validate the theoretical methods and to explore the application of advanced technology rotor systems. This capability is provided by a Mach-scaled model rotor rig, which, combined with a purpose built hover facility used with the DERA 24-ft and 5-m wind tunnels, forms an integrated test capability covering the flight envelope of the helicopter.

France and Germany have expertise in bearingless rotor hubs. Germany also has noteworthy capabilities in composite materials and high-strength alloy shafting.

The Sadlier VTOL Aircraft Co. PTY, Ltd., of Australia is considering a vertical take-off aircraft that would combine the properties of fixed-wing and rotary-wing aircraft. It has a fan in the wing and a rear fan. It employs a diamond-shaped lift system with a single lift rotor at the center of the fan.

Country	Gas Turbine Engines	Other Aeronautical Power Sources	Fuels Technology
Australia		●●●	
Canada			●●
China	●	●	
France	●●●●	●●●	●●
Germany	●●●●	●●●	●●
India		●	●
Israel	●●	●●●	
Italy		●	
Japan	●●●	●●●	●●
Russia	●●●●	●●●●	●●●●
Sweden	●●	●●	●●
Switzerland	●●		●●
UK	●●●●	●●●●	●●●
United States	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 1.2-3. Aeronautical Propulsion Technology WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-1.2. AERONAUTICAL PROPULSION

DATA SHEET III-1.2. CERAMIC MATRIX COMPOSITES (CMCs)

Developing Critical Technology Parameter	Develop CMCs to withstand increases in combustor temperatures and turbine blades to 2,500 °F without the requirement for cooling.
Critical Materials	SiC/SiC; Silicon nitride.
Unique Test, Production, Inspection Equipment	Non-Destructive Evaluation (NDE) methods for new and fielded CMC components.
Unique Software	None identified.
Technical Issues	Ductility, durability, crack growth requirements, and affordability. An accurate failure mechanism prediction and crack growth rate. Turbine blade attachment contact stresses are high because of the high heat transfer from the blade to the disk rim. Contact stresses need to be reduced for increased service life. High Weibel modulus (run with a crack).
Major Commercial Applications	Civil aviation and industrial gas turbine engines.
Affordability	Advanced fabrication and joining methods, fiber costs. Performance/cost trade will become favorable with further development.

RATIONALE

CMCs have been identified as potential candidates for high-temperature structural applications because of their high-temperature strength, light weight, and excellent corrosion and wear resistance. CMCs are used in gas turbine hot section components and exhaust nozzles. Their high-temperature capability improves engine performance, thrust-to-weight ratio and specific fuel consumption (SFC) by reducing the need for cooling air.

Uncooled ceramic turbine blades will allow the turbine inlet temperature to be increased without the associated cooling penalty of increased weight. This provides a significant increase in turbine efficiency and power. Uncooled combustor liners will allow improvements in allowable cycle temperature, combustion efficiency and reduced unwanted exhaust emissions. CMCs that withstand high combustor operating temperatures reduce aircraft weight and subsequently increases range/payload.

Civil aviation and industrial gas turbine engines can use this technology.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●●	France	●●●●	Germany	●●●●
Japan	●●●	Russia	●●●	South Korea	●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

France [Societe Europeenne de Propulsion (SEP)] leads composite design and fabrication technology. Japan leads in ceramic fiber technology.

- ***Canada***

Concordia Centre for Composites is doing fundamental and applied work in ceramic matrix composites.

- ***Russia***

  Russian Academy of Sciences, Laboratory of Reinforced Systems of Solid State Physics Institute is engaged in a study of elastic-plastic and creep behavior of composite materials with metal and ceramic matrix.

- ***South Korea***

  Korea Advanced Institute of Science and Technology (KAIST) is doing work with metal matrix composites for aerospace applications.

DATA SHEET III-1.2. COOLED COOLING AIR

Developing Critical Technology Parameter	Lightweight, low-volume heat exchangers with a temperature differential between inlet and outlet of approximately 400 °F. Heat exchanger compactness: 0.5 W/cm^3-K.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Diffusion bonding technology.
Unique Software	None identified.
Technical Issues	Safety; cost; fuel thermal stability (oxidation); weight of a high-efficiency heat exchanger.
Major Commercial Applications	Next generation turbofans (high operating ratio); nuclear reactors; environmental control systems.
Affordability	Extends capability of current materials used in compressor disks, turbine blades, and vanes if heat exchanger technology does not impose weight and volume penalty.

RATIONALE

Using fuel/air or air/air heat exchangers to provide lower temperature cooling air for the turbine and the compressor disks allows current cooled materials to operate at higher engine-cycle temperatures without an increase in metal temperature. High-performance combat aircraft can operate at higher compressor exit (high operating ratio, high Mach number) and turbine inlet temperatures to improve specific power and fuel consumption.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●	Germany	●●	Japan	●●
Russia	●●●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Two Russian military engines use air/air cooling (fan duct heat exchangers). Pratt & Whitney is developing an engine with fan duct heat exchangers for the JSF.

DATA SHEET III-1.2. FLUIDIC NOZZLE

Developing Critical Technology Parameter	Thrust vector angle and rate changes to provide maneuvering with minimum airfoil control effectors. Nozzle weight reduced 50 percent; a 70-percent reduction in overall parts count.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Maximum thrust vector angle and rate of change capability; thrust coefficient; secondary airflow quantity; air vehicle integration and installed performance; integrated flight/propulsion controls; design methodologies for fully-fixed exhaust system for after-burning jet engine application.
Major Commercial Applications	Low potential; possible technology application to civil transport aircraft (lower noise).
Affordability	Lack of moving parts and the simplified structural integration combine to improve nozzle maintainability and reduce life-cycle cost.

RATIONALE

Fluidic thrust vectoring is the deflection of the exhaust thrust vector of a jet engine through the influence of a secondary fluid stream. This technology allows for a fixed nozzle that will reduce weight and complexity of current variable area convergent/divergent nozzles. Currently used mechanical vectoring and area-control systems add weight and complexity to aircraft exhaust systems.

Fluidic nozzles are expected to provide increased maneuverability along with the reduction/elimination of conventional control effectors. The reduction of these effectors will also provide for decreased radar signature. The potential for jet plume mixing will also support the reduced signature objectives to include (potentially) infrared (IR) signatures.

Fluidic nozzles are applicable to tactical aircraft that have aggressive survivability requirements. Conformal fluidic nozzles provide after-burning and pitch/yaw thrust vectoring capabilities, with significant reductions in nozzle weight when compared with the pitch-only vectored F-22 nozzle. To maximize benefits, the nozzle must be paired with a variable-cycle engine (as opposed to a fixed-cycle engine).

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●●	Germany	●●●	Israel	●●
Japan	●●	Russia	●●●	Sweden	●	Switzerland	●●
UK	●●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States, DoD, academia, and industry are advancing this technology. Any nation with the technology to develop advanced engines for fighter aircraft is capable of incorporating fluidic nozzle technology.

DATA SHEET III-1.2. HIGHER BLADE-COOLING EFFECTIVENESS

Developing Critical Technology Parameter	Blade-cooling effectiveness (θ) greater than 0.75 and cooling parameter less than 2 ($\bar{\omega}$) (see Figure 1.2-4); turbine inlet temperature greater than 2,500 °F.
Critical Materials	Advanced single-crystal materials.
Unique Test, Production, Inspection Equipment	Core fabrication; casting process; core removal; inspection process.
Unique Software	None identified.
Technical Issues	Fragile, complex core geometry; reactions between cores and alloy; thin wall casting yields; test and production equipment.
Major Commercial Applications	Next-generation turbofans.
Affordability	Extended hot section life.

RATIONALE

Increasing turbine inlet temperature allows engines to produce more thrust, but the key is having in the hot section the materials that can to withstand the very high temperatures. Achieving this requires new technology in materials and better cooling methods. A methodology has been derived by which the many parameters involved can be lumped into a relationship between cooling effectiveness (θ) and a cooling parameter ($\bar{\omega}$) (see Figure 1.2-4).

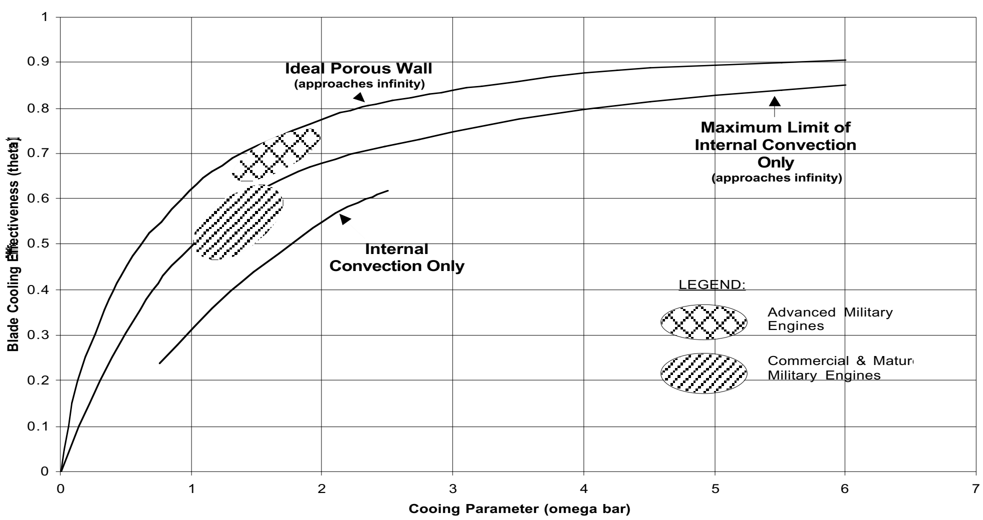

Figure 1.2-4. High-Power Turbine Blade-Cooling

The most efficient designs, from an overall performance standpoint, are those that achieve the highest cooling effectiveness at the lowest possible cooling parameter. High-performance engines would operate at higher cycle temperatures without additional penalty caused by increased cooling flows.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Germany	●●●	Japan	●●●	Russia	●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A 2,500-°F temperature represents the level of turbine inlet temperature in new model Russian front-line fighter engines at rated power. The United States holds the edge in turbines designed to operate at turbine inlet temperatures above 2,500 °F.

DATA SHEET III-1.2. INTERMETALLIC TURBINE BLADE

Developing Critical Technology Parameter	Turbine blades that can achieve increased performance through reduced blade weight and material capable of higher temperatures (to 2,500 °F).
Critical Materials	TiAl, NbAl, molybdenum disilicide, and niobium disilicide.
Unique Test, Production, Inspection Equipment	Being developed.
Unique Software	Not identified.
Technical Issues	Manufacturing technologies.
Major Commercial Applications	Fixed- and rotary-wing commercial aircraft that use gas turbine engines.
Affordability	Increased turbine life.

RATIONALE

Turbine blades have historically been manufactured from castings. Use of intermetallics for weight savings imposes additional structural requirements and design complexities (double-walled spar design), which change the turbine-blade fabrication technology.

Intermetallic turbine blades can result in an increase in component efficiencies and high operating-temperature capabilities through reduced turbine weight. They can be used in fixed- and rotary-wing military aircraft that have gas turbine engines.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	China	●	France	●●●	Germany	●●●
India	●●●	Japan	●●●	Russia	●●●	South Korea	●
Sweden	●●	Switzerland	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

- ***Australia***

  The Melbourne Research and Innovation Office at the University of Melbourne is working on the development of inter-metallic alloys for high-temperature applications.

- ***India***

  The National Aerospace Laboratories have down work on an electrochemically assisted arc machine (ECAAM) for turbine-blade machining and machining of intermetallics.

DATA SHEET III-1.2. MAGNETIC BEARINGS

Developing Critical Technology Parameter	Magnetic (non-lubricated) bearings that can maintain or improve on the loads and environmental conditions (available in current bearing technology).
Critical Materials	Superconducting materials at high temperatures or magnetic materials that maintain high flux density at temperatures up to 1,000 °F. Robust, high-temperature insulation material that can be easily thin-coated onto magnetic coil windings.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	5-axis control feedback.
Technical Issues	Robust insulation coatings for magnetic coil windings; elimination of mechanical backup for electrical power failure; system weight and bulk; redundant controls and power supplies; graceful failure mechanism; temperature and load-carrying ability; weight; transient load capability; affordability.
Major Commercial Applications	First applications for marine and industrial; turbine, generator, and automotive industry.
Affordability	Until this technology is mature and many units are produced, magnetic bearings will be less affordable than conventional bearings. Elimination of lubrication circuits will reduce leaks and servicing requirements.

RATIONALE

Active magnetic bearings are used to support a rotating shaft (e.g., that in a gas turbine engine) in a magnetic field. This provides many advantages over ordinary bearings because there is no contact between the shaft and the housing. There is, therefore, no wear, and no lubrication is required.

Magnetic bearings simplify the lubrication system and allow higher temperatures, active rotor (engine shaft) control, and higher performance engines. Logistics savings area also realized because of no lubrication requirements, less maintenance, and higher reliability.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	Finland	●●	France	●
Germany	●●	Israel	●●	Japan	●●●	Russia	●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Magnetic bearings are being closely evaluated for small aircraft, ground-vehicle, and sea-platform applications because of potential performance and control benefits. Advanced R&D is being done for use in large, man-rated aircraft engines, but fielded application is probably at least 10–20 years away.

In the United States, the University of Virginia has a Center for Magnetic Bearings. The University of Sheffield in the Untied Kingdom is conducting research on magnetic bearings. In Finland, the Laboratory of Electromechanics at the Helsinki University of Technology has conducted research on magnetic bearings.

DATA SHEET III-1.2. PULSE-DETONATION ENGINES (PDEs)

Developing Critical Technology Parameter	Air-breathing PDEs: practical design configurations without pre-detonator or required pre-detonator volume less than 2 percent of total detonation tube. Operating frequency above 40 Hz per detonation tube.
Critical Materials	High-temperature materials for uncooled propulsion structures.
Unique Test, Production, Inspection Equipment	Supersonic/hypersonic testing of integrated inlet-combustor-nozzle over a wide range of simulated flight conditions (altitudes and Mach numbers).
Unique Software	CFD; optical diagnostic techniques; ultra high-speed framing Schlieren photography.
Technical Issues	Ability to generate and control repeated, consistent detonations in practical design configurations; minimization of performance losses from inlet and nozzle integration that would offset the benefits of detonation combustion; accurate modeling of detonation phenomena; vehicle integration and high mass-flow rapid and robust valves.
Major Commercial Applications	Space-launch vehicles.
Affordability	Air-breathing PDEs have the potential to be much simpler—hence, less expensive—than gas turbine engines for similar performance levels.

RATIONALE

NASA's long-term space transportation research is directed toward high risk, breakthrough technologies, such as PDEs, high-energy propellants, and advanced propulsion concepts and materials. PDEs present novel alternatives to current gas turbine and rocket engines, based on a continuous combustion process. PDE technology has the potential to achieve higher performance at lower cost than gas turbine engines.

Advantages of PDEs include high efficiency, mechanical simplicity, compact size, and near instantaneous start, spool-up, and throttling. A detonation in a tube serves as the PDE's combustor. The detonation rapidly traverses the chamber, resulting in a nearly constant volume, heat-addition process that produces a high pressure in the combustor to provide thrust. By operating multi-tube configurations at high frequencies, near-constant thrust can be produced. PDEs are also easy to maintain, demonstrate high thrust-to-weight ratios, and have significantly lower SFC compared with other engine types producing similar thrust.

Pulse detonation is an enabling technology for multi-mode propulsion systems for military aerospace vehicles. NASA has constructed two PDE test articles and has begun initial tests to demonstrate the engineering feasibility of rocket engines based on this promising technology. Small (5-cm) PDEs could be used in MAVs. They could also find possible use in precision-guided standoff munitions, cruise missiles, and unmanned aircraft.

The concept of pulse detonation has existed since the 1940s. Advances in computational capability and experimental diagnostics appear to be ready to enable the development of practical PDEs burning liquid fuels in air.

WORLDWIDE TECHNOLOGY ASSESSMENT

Israel	●●●	Japan	●●●	Russia	●●●	Sweden	●●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Efforts are underway, or have been conducted recently, in Israel, Japan, Russia, Sweden, and the United Kingdom. Meridian International (United Kingdom) has studied the whole spectrum of research, development, and future advances in the field of aerospace propulsion, including PDEs. Efforts in Israel and Russia appear to be at a comparable state of the art. Otherwise, foreign technology development efforts are apparently less mature than U.S. activities.

Individual science-level efforts on detonation-wave phenomena and modeling may be superior (especially in Russia). The California Institute of Technology's Explosion Dynamics Laboratory has conducted experiments on detonation initiation, which has application to PDEs. The University of Texas and Penn State University have also conducted PDE research. Adroit Systems, Inc., has seven patents supporting its PDE development work in the Seattle, Washington, area.

DATA SHEET III-1.2. RAMJETS/SCRAMJETS

Developing Critical Technology Parameter	Air-breathing engines to operate at speeds in excess of Mach 5.
Critical Materials	High-temperature materials.
Unique Test, Production, Inspection Equipment	Hypersonic wind tunnel engine test capability.
Unique Software	None identified.
Technical Issues	Scramjet: engine thermal protection, flow turbulence, shock wave/boundary layer interactions, and boundary layer transition; design of the fuel injection system.
Major Commercial Applications	Supersonic transport (SST); high-speed civil transport (HSCT); space-launch vehicles.
Affordability	Ramjet/scramjet engine would be cheaper than gas turbine engines. Vehicle development/integration will dictate cost (expensive).

RATIONALE

Ramjets/scramjets enable flight at velocities greater than that which gas turbine engines can achieve. Ramjets are limited to about Mach 6. The upper speed limit of scramjets has yet to be determined, but theoretically it is above the range required for orbital velocity (Mach 20 to 25). Practically, however, material structural considerations and combustion efficiency limit the maximum speed to about Mach 15. Combined-cycle turbine/ramjet/scramjet/rocket engines could allow a hypersonic, aeronautical vehicle to take off, go into orbit, and strike targets anywhere in the world within hours. Ramjets have demonstrated readiness for the next generation beyond-visual-range missiles.

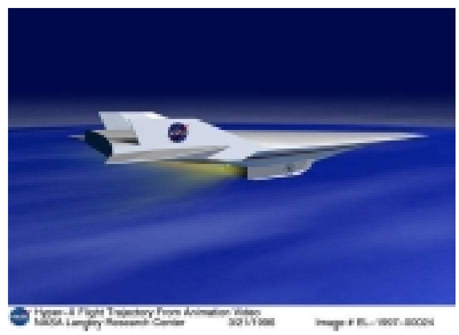

Figure 1.2-5. X-43A (Hyper-X)

Military applications of scramjet technology include long-range reconnaissance and rapid-strike missions Operation at hypersonic velocities allows CONUS-based surveillance missions within hours of request and multiple passes without the predictability of satellite orbits. High speed and altitude supplant expensive stealth technology to achieve survivability for hypersonic vehicles and cruise missiles.

Figure 1.2-6. Scramjet Strike Missile

Through its Hyper-X research program at Langley and Dryden Research Centers, NASA is currently building the X-43A (see Figure 1.2-5), a 3.6-m-long aircraft that will demonstrate scramjet flight at Mach 7 and Mach 10 within the next 3 years. Scramjets could also improve missile range (see Figure 1.2-6) and could be used to power reusable space launch vehicles that would weigh less, carry more payloads than conventional rocket launch systems, and operate from existing runways anywhere. This increases U.S. forces' access to space and their ability to place satellites into any orbit on demand, thus ensuring communications and surveillance.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	China	●●	France	●●●●	Germany	●●●●
India	●●	Israel	●●●	Italy	●●	Japan	●●●●
Russia	●●●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan has an independent Hypersonic Propulsion Technology Program (HYPR) program. The HYPR program is funded by the New Energy and Industrial Technology Development Organization (NEDO). Technology such as this will be required for the next generation of super/hyper-sonic transport propulsion system. The Institute of Space and Astronautical Science (ISAS) Propulsion System Laboratory, in Japan, has studied an expander cycle air-turbo ramjet engine, "ATREX," as a candidate for the propulsion system of the fly-back booster of the two-stage-to-orbit space plane. The Noshiro Rocket Testing Center, one of the facilities of the ISAS of the Japanese Ministry of Education, has conducted ground-firing tests to check the performance of the air turbo ramjet (ATR) engine.

In addition to Japan, France and Germany have well-funded programs for the development of next-generation hypersonic vehicles. Aerospatiale (France) produces ramjet equipment (electrovalves, injectors, air intakes, motor bay assemblies, and so forth). The first French ramjet was released over Blagnac and reached a speed of 700 km/h in April 1949. Today, the Office National d'Etudes et de Recherches Aerospatiales (ONERA) (France) cooperates with the Russian Central Aero- and Hydrodynamic Institute (TsAGI)[1] and Central Institute of Aviation Motors (CIAM) for aerodynamics and ramjet propulsion.

According to *Scientific American,* Australia, France, Germany, Japan, Russia, and the United Kingdom have performed ground tests of prototype scramjet engines, and other related research is underway in countries such as China, India, and Italy. Today, scientists routinely conduct ground tests of scramjet engines at simulated speeds up to Mach 15. In flight tests, the Russians have demonstrated ramjet operation of a dual-mode scramjet up to Mach 6.4. NASA is currently building the X-43A (see Figure 1.2-5) that will demonstrate scramjet flight at Mach 7 and Mach 10 within the next 3 years.

China is developing ramjet engine technologies to confer supersonic speeds on its missiles, and this will complicate interception. In addition, ramjets offer the potential to increase the range of a smaller missile. China's existing ramjet-powered missiles are large and cannot travel great distances, but the purchase of the operational Russian Raduga SS-N-22 ramjet-powered antiship missile could provide China a new source of cruise missile ramjet technology.

Aerospatiale has a contract from the French Defense Procurement Agency (DGA) covering the predevelopment of a new generic supersonic missile powered by a liquid-fueled ramjet engine. The VESTA (Vecteur à Statoréacteur) will form the basis for the future antiship missile ANNG (Anti-Navire Nouvelle Génération).

BACKGROUND

The ramjet engine, which was invented in France in 1913, is the simplest type of the all-jet engines because it has no moving parts. It achieves compression of intake air by the forward speed of the air vehicle. The aerodynamic diffusion created by the inlet and diffuser slows the air entering the intake of a supersonic aircraft to velocities comparable to those in a turbojet augmentor. The expansion of hot gases after fuel injection and combustion accelerates the exhaust air to a velocity higher than that at the inlet and creates positive push. The ramjet has to be traveling through the air at high speed before it can be started; therefore, it has to be boosted to the proper speed by some other type of propulsion. In theory, the ramjet engine has no maximum speed and can accelerate indefinitely as long as it stays within the atmosphere. In reality, ramjets are limited to about Mach 6, above which the combustion chamber becomes so hot that the combustion products (water) decompose. The biggest drawback of the ramjet engine is its high rate of fuel consumption.

[1] TsAGI is the Russian equivalent of NASA.

Scramjet is an acronym for supersonic combustion ramjet. The scramjet (see Figure 1.2-7) differs from the ramjet in that combustion takes place at supersonic air velocities through the engine. By not slowing down the engine airflow to subsonic speeds for combustion (as in a ramjet), scramjet engines can operate more efficiently at Mach numbers above 5. It is mechanically simple, but more complex aerodynamically than a jet engine. The biggest structural challenge of a scramjet engine is thermal protection of the internal engine walls and fuel injector components.

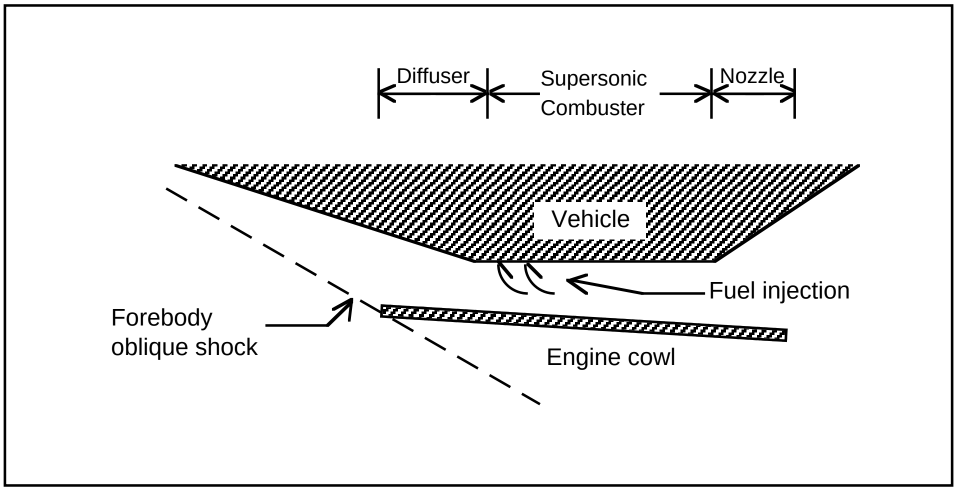

Figure I.2-7. Scramjet Diagram

Scramjets or ramjets can use a variety of cryogenic or storable fuels. Hydrogen fuel offers the highest specific impulse but requires cryogenic tankage and fuel-handling capabilities (see Data Sheet on Cryogenic Fuels, page III-1-46). During the 1990s, substantial progress was made on the development of storable hydrocarbon fuels that use chemical bond breaking (endothermic reaction) in the presence of catalysts to double the heat sink capability of the fuel from its physical heat sink alone. This breakthrough allows the scramjet engine thermal balance to be sustained up to Mach 8 flight by using fuel cooling of the combustor components (see Data Sheet on Endothermic Fuel-Cooled Technology, page III-1-49).

DATA SHEET III-1.2. CRYOGENIC FUELS

Developing Critical Technology Parameter	Achieving hypersonic (above Mach 6) or very long-range capability.
Critical Materials	Graphite epoxy composites.
Unique Test, Production, Inspection Equipment	Cryogenic fuel measurement system.
Unique Software	None identified.
Technical Issues	Temperature variation and hydrogen compatibility; handling cryogenic fuel including infrastructure investment; leak detection.
Major Commercial Applications	SST, HSCT, space launch; heavy duty trucks, buses, and automobiles.
Affordability	Large cost for demonstration and development but enables the use of fully reusable space-launch vehicles and long-range strike missiles from tactical aircraft.

RATIONALE

Cryogenic fuels enable hypersonic flight and will be used in the future for reusable launch vehicles (RLVs). These fuels are also being evaluated as alternative fuels for the trucking industry. Trucks transport cryogenic fuels, and investigations are underway to see if they can also burn them.

Boeing Rocketdyne is developing and building the XRS-2200 for the X-33 and is planning a full-scale RS-2200 for the future VentureStar orbiter. Both engine variants use liquid oxygen and liquid hydrogen for the highest possible performance, placing them in the group of modern cryogenic high-performance engines.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	France	●●●	Germany	●●●●	India	●●●
Israel	●●	Italy	●●	Japan	●●●	Russia	●●●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

India is developing a cryogenic-fuel-driven geosynchronous satellite launch vehicle (GSLV). The three-stage GSLV, equipped with an upper cryogenic fuel state, is designed to orbit 2.5-ton communications satellites into a geosynchronous orbit. Germany is testing a liquid hydrogen automotive service station at Munich International Airport and leads the world in developmental work on hydrogen technology for use as an automotive fuel. Russia's A.N. Tupolev Scientific and Technological Aviation Complex (Tupolev ANTK) claims it has solved all technical problems in the field of cryogenic aircraft fuels. The company has a unique gas facility for the Tu-156 series experimental aircraft at the Gromov's Flight Test and Research Institute in Zhukovsky.

BACKGROUND

Cryogenics is the science of very low temperatures. An accepted temperature used to distinguish between refrigeration and cryogenics is –73.3 °C (–100 °F). Low temperatures in the cryogenic range are generally obtained by the liquidification or solidification of gases. The boiling point of liquid hydrogen is –252.7 °C.

In Russia, Kriogenmash AO is involved in cyrogenic fuels. The company originated in 1949 when the Plant of Cryogenic Machine-building was built in Balashikha. The company was involved in all missiles and launchers, featuring cryogenic fuel components (i.e., missiles: V-2/R-1 to the R-9 and SLVs from R-7/8A91 to the Energia-Buran system).

Kriogenmash AO's principal directions of activity include research, development, production, and assembly of:

- Air-fractioning, gas-fractioning, and liquefying installations for the production of oxygen, nitrogen, argon, hydrogen, liquid natural gas, crypton, xenon, neon, and so forth
- Systems for storage, transportation and fueling of liquid cryogenic products (oxygen, nitrogen, argon, hydrogen, natural gases, and helium)
- Space simulators and cryogenic thermal vacuum chambers for the aviation, rocket and space technology, medicine, radioelectronics, optics, food, and pharmaceutical industries
- Helium systems, liquefiers, and refrigerators for cooling objects in the temperature range 0.35–4.5 K.

Currently, Kriogenmash AO participates in the experimental development projects under the Federal Space Program of Russia.

DATA SHEET III-1.2. NEW-CAPABILITY FUELS

Developing Critical Technology Parameter	Fuels that function at higher temperatures with increased performance and stability for turbine engines.
Critical Materials	Various additives; composition and synthesis techniques of additives, initiators, catalysts, and coagulation and soot suppressants.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Development of various additives that increase fuel stability while decreasing fuel coking; performance of additives to reduce hydrocarbon fuels ignition delay, emissions, and/or signature or improve engine and/or aircraft operability as a function of military combustor conditions, including pressure, temperature, residence time, and equivalence ratio.
Major Commercial Applications	Increased fuel heat sink for aircraft designed to take advantage of higher fuel-tank temperatures and reduced engine coking; all present and evolving military and civilian aircraft.
Affordability	Projected cost is pennies per gallon. Requires but a small amount of additive.

RATIONALE

High-temperature fuels increase the potential heat that can be put into the fuel and reduces the amount of coking experienced in the engine; however, hydrocarbon fuels have long ignition delays and form particulates in engine exhaust that increase visibility (signature) and have harmful health and environmental effects. Therefore, chemical additives that enhance ignition/mitigate emissions and particulates must be applied at cost-effective, parts per million (ppm) concentrations. The addition of a small amount of additive(s) in the fuel costs only pennies per gallon. The reduced coking in the engine significantly reduces aircraft life-cycle costs.

Chemical additives that will enhance ignition and mitigate particulate formation in military and commercial engines are the subjects of ongoing investigations. Meeting this objective will enable the sustainment of military readiness and allow both the military and commercial sectors to meet the air-quality standards of the Clean Air Act Amendments (1990) and upcoming amendments to this act.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●●	Germany	●●●	Japan	●●
Russia	●●●	Sweden	●●	Switzerland	●●	UK	●●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The JP-8+100 additive has been shown to mitigate particulates in limited operational engine tests. JP-8+100 is improved JP-8 fuel with a "fuel injector cleaner" (additive) that reduces fouling/coking in engine fuel controls, mainburner fuel nozzles, manifolds and augmentor sprayrings/spraybars and reduces smoke and soot in older engines. JP-8+100 will reduce engine and aircraft fuel system operation and maintenance costs for current and future aircraft.

DATA SHEET III-1.2. ENDOTHERMIC FUEL-COOLED TECHNOLOGY

Developing Critical Technology Parameter	Heat sink [e.g., British Thermal Units (BTUs/lb)] as a function of fuel conditions—temperature, residence time, pressure, and so forth; increased vehicle thermal management capacity.
Critical Materials	Catalysts, coke-inhibiting structural materials; coatings (initiators and inhibitors); anticoagulant additives.
Unique Test, Production, Inspection Equipment	Production of structures and engines that incorporate fuel passages for cooling.
Unique Software	Flow-control software to ensure proper temperature of flow before it enters combustor.
Technical Issues	Deposition (coking) from high-temperature fuels; catalysts and catalyst attachment methods; coke-tolerant structures/designs; operability of engine when fuel properties vary from liquid to vapor over envelope, heat exchanger design; manufacturing technology; vehicle fuel and thermal management integration; reactor fuel-flow control/ regulation.
Major Commercial Applications	Hydrocarbon-fueled hypersonic vehicles (none at present); launch vehicles and HSCT.
Affordability	Enables the use of fully reusable space-launch vehicles and long-range strike missiles from tactical aircraft.

RATIONALE

Endothermic fuels undergo endothermic (heat-absorbing) chemical reactions while flowing through heat exchangers and fuel-cooled structures. They are an enabling technology for hypersonic, storable-fuel, scramjet engines (Mach 5–8). The heated and decomposed chemical byproducts of the endothermic process also aid in mixing and in a supersonic stream that result in combustion efficiencies greater than 90 percent.

Coke deposits, or carbon build-up, occur when hydrocarbon fuels are locally heated to high temperatures (> 1,000 °F). In endothermic fuel reactors/heat exchangers, this can reduce contact with catalytic surfaces and result in lower endothermic efficiency and increased pressure drop through the flow passages. Periodic maintenance to remove this buildup is feasible for reusable systems, but sustained operation at the maximum upper fuel temperature coking limit can result in local overheating of structural components.

WORLDWIDE TECHNOLOGY ASSESSMENT

Russia ●●● United States ●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Thus far, only the military has used endothermic fuel technology. These fuels have been ground-tested only (United States, Russia). No flight tests have been conducted.

Russia has conducted extensive testing of fuel additives and initiators to lower the temperature at which the endothermic cracking process begins. This technique can result in higher heat transfer rates and lower structural operating temperatures of cooled engine components.

BACKGROUND

Endothermic fuel technology using operational jet propulsion (JP) fuels has been under development primarily by NASA and the Air Force since the early 1970s. Fuels tested for endothermic cooling capabilities and scramjet engine combustion include JP-7, -8, -10, NORPAR-12, and methylcyclohexane (MCH). Various catalysts are used to enhance the endothermic process, and several catalytic heat exchanger/reactor (CHER) designs and material systems have been developed and tested. Recently, low-cost catalytic coating processes have been successfully demonstrated on complex scramjet engine heat-exchanger and fuel-injector components.

SECTION 1.3—AERONAUTICAL STRUCTURES

Highlights

- Smart structures and materials will enable a new generation of vehicles that have highly integrated structures and actuators.
- On-board health monitoring systems will reduce time between removal and replacement of structural components.
- Active load control will result in increased service life and reliability.

OVERVIEW

This section covers production techniques and methodology, maintenance technologies, and in-flight technologies associated with the air-vehicle structures. It does not include the development and production of materials used in the structures but rather the application and the processes necessary to fabricate and assemble the end-use structures. These structures may be applicable to any and all parts of an air vehicle, including lifting surfaces and bodies and other subsystems and components.

RATIONALE

A continuing and enduring objective in developing and building aeronautical structures systems is attaining high-strength properties that have the ability to withstand environmental, stress, and other outside forces while minimizing weight. Often, these characteristics are achieved through special materials and alloys, yet the structures' qualities can also be improved through design and manufacturing techniques. These processes must be optimized to achieve the full capability of the advanced materials being used.

The technologies in this section aim to improve aircraft structural performance while reducing acquisition and operating costs. Virtual prototyping to optimize structural design for efficiency and performance is of particular interest. It will remove a large portion of the risk involved in exploring new concepts and moving rapidly from concept to production. Reducing dynamically loaded, structural stress prediction inaccuracy and the production labor hours per pound for composite structures are other areas of great interest. Breakthroughs in these and other areas will improve maintenance and production costs, reduce the empty weight fraction of the airframe, and increase durability, performance, and ride comfort.

WORLDWIDE TECHNOLOGY ASSESSMENT (see Figure 1.3-1)

The United States has always been a leader in the production of high-strength, lightweight, durable structures. Other nations—Russia specifically—have often approached the strength question with robustness of design to ensure adequacy where weight was a secondary objective.

Advanced composite structures are becoming common in international aircraft. Technologies for rotary-wing military systems reside primarily in the few countries that produce military helicopters. Predominant among these are France, Germany, Italy, and the United Kingdom. The United Kingdom has strong capabilities in composites and smart structures. Crash survivability is an area of special interest. France has expertise and, in general, is on a par with the United States in this area. Survivability depends on several factors, including equipment performance, which can be improved by more efficient design and testing of aircraft structures. Of particular interest is the testing of advanced structural concepts and manufacturing processes for composite and thermoplastic materials for primary helicopter airframe structures. In addition to the aforementioned countries, Canada has strong capabilities in fracture/fatigue analysis, Russia has strong capabilities in titanium and steel alloy structures, and Japan has world-class expertise in ceramics and composite materials.

Country	Production Techniques and Methodology	Maintenance Technologies	In-Flight Technologies
Australia	●	●●	
Canada	●	●●	●
China	●	●●●	●
France	●●●	●●●	●●●
Germany	●●●	●●●	●●●
Israel	●		●●
Italy	●●		●
Japan	●●●	●●●●	●●●
Netherlands	●	●●	
Russia	●●	●●●	●●●
South Korea	●		
Sweden	●	●●●	●●●
Switzerland	●		●●
UK	●●●	●●●	●●●
United States	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 1.3-1. Aeronautical Structures Technology WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-1.3. AERONAUTICAL STRUCTURES

DATA SHEET III-1.3. CONFORMAL LOAD BEARING ANTENNA STRUCTURES

Developing Critical Technology Parameter	Elimination of 100 percent of the drag associated with externally mounted antennas.
Critical Materials	Materials providing structural and dielectric properties; radome materials having strength and stiffness yet providing low dielectric and magnetic loss. Materials exhibiting high dielectric and/or magnetic loss, while matched to free-space impedances, would provide critical antenna-loading capabilities.
Unique Test, Production, Inspection Equipment	**Test:** Equipment that tests the electrical performance of the antennas while subjecting the device to the environment (e.g., heat, stress, reduced air pressure, increased water pressure, vibration, structural loads, and so forth). **Production:** Similar test equipment with increased throughput. **Inspection:** Hand-held, portable, or increased speed test equipment that performs checks on the test functions.
Unique Software	Software linking multiple antennas, or antenna array elements, would aid the development of conformal, load-bearing antennas. Any software that could, in real time or near-real time, provide control, analysis, or synthesis functions to reconstruct direction or identification of type of the energy incident upon the antennas would provide critical developmental technologies.
Technical Issues	Professional people trained in electromagnetic propagation; mechanical/structures analysts with an understanding of magnetic and dielectric material properties provide the essence of those people required for design; chemists, with an understanding of dielectric material properties. Software programs providing finite element analysis, both electrical and mechanical (including material properties), from a common computer-aided design (CAD) database would drastically improve the speed of creating realizable designs. Crossed-slot antennas are best suited for this application (efficient volumetric utilization and wide gain patterns) but have been poorly modeled. Systems with graded aperture width or loading are difficult to analyze with available tools, but these features may be required to obtain optimal bandwidth efficiency in electrically small devices.
Major Commercial Applications	Could be applied to commercial vehicles currently constrained in performance by the current sensor's field of view caused by vehicle structures or outer mold line constraints.
Affordability	Affordability can occur by reducing the number of sensors necessary (because of increased efficiencies in field of view) and by reducing life-cycle cost [sensors capable of structural integrity will have increased mean time between failures (MTBFs)].

RATIONALE

This technology provides capability in placing antennas (sensors) in places on vehicles previously denied because of structural and/or aerodynamic reasons. Integration of load-bearing, conformal surfaces that provide electromagnetic sensing functions reduces the number of new sensors and increases the new sensor's field of view.

In addition to providing LO conformal antennas, capability exists for integration of multiple apertures serving varied needs [e.g., ultrahigh frequency (UHF) communications (COM)/satellite communication (SATCOM), Global Positioning System (GPS), identification friend or foe (IFF), and so forth] within a common housing, which would provide significant space and weight savings. Potential beneficiaries of this technology are JSF, Comanche, FA-18E/F, and other aircraft with sensitive RCS requirements. By structuralizing the aperture, integration of the antenna into existing airframes is greatly simplified**.**

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●●	China	●	France	●●●
Germany	●●●	Israel	●●●	Italy	●●	Japan	●●●
Netherlands	●●●	Russia	●●●	Sweden	●●	Switzerland	●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Slot-antenna characterization, because of its inherent benefits, has probably been studied by all nations with advanced aircraft. Electrically small apertures have been similarly studied, but efficient wideband performance with minimal cavity volume has probably not been realized yet except by extensive finite-element modeling and cut-and-try experimentation. In the Netherlands, the National Aerospace Laboratory (NLR) is conducting research to determine the electromagnetic interaction of conformal antennas with the aircraft structure.

DATA SHEET III-1.3. SMART STRUCTURES/MATERIALS

Developing Critical Technology Parameter	Smart structures will reduce the air vehicle empty weight by 10 to 25 percent.
Critical Materials	SMAs and actuator forms; ferroelectric ceramics, particularly single crystal variants of piezoelectric ceramics.
Unique Test, Production, Inspection Equipment	Test equipment and particularly standardized *test methods* to provide total life/performance data under realistic loading (mechanical, thermal, and electrical) conditions; production equipment for large-scale, low-cost production of high-quality piezoceramics, particularly single crystal and fiber forms.
Unique Software	Modeling piezoceramics, including effects of aging and use at high field levels; three-dimensional (3-D) modeling of SMAs, including shear.
Technical Issues	Development and demonstration of complete actuator systems, including displacement amplification, power, and control; flight test demonstrations to increase credibility; new actuation techniques, such as rectification and termination methods, for high force SMA actuators; highly robust and self-adaptive control techniques.
Major Commercial Applications	Medical applications of SMAs; piezoceramics for speakers, ultrasonic transducers, and sensors.
Affordability	Active fibers are highly promising but not currently affordable. SMAs are generally affordable unless temperatures above about 90 °C are required. Then, expensive doping materials (Pd, Pt, Hf) are required.

RATIONALE

Smart structures and materials technology will enable a new generation of vehicles that have highly integrated structures and actuation systems. This will free up internal volume for payload or fuel. Metamorphic or shape change structures will enable vehicles to operate at near optimal performance over a very broad flight envelope, thus enabling new missions and multimission vehicles. Active vibration, acoustics, and load suppression will reduce the cost and extend the lives of conventional vehicles through reduced design and qualification requirements on avionics (enabling use of COTS avionics) and of vehicle structures. Smart structures will assist in flutter suppression.

WORLDWIDE TECHNOLOGY ASSESSMENT

Argentina	●	Australia	●	Canada	●●	China	●
France	●●	Germany	●●●	Israel	●	Italy	●●●
Japan	●●●●	Netherlands	●	Russia	●●	South Korea	●●
Switzerland	●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There has been a large proliferation of international conferences in this technology. The United States is currently the overall leader in this technology, but significant research efforts are ongoing in Japan and Europe, often for nondefense applications. In some nondefense applications, Japan and Europe possess at least parity—if not a technological lead over the United States.

The Canadian National Research Council conducts and coordinates a wide range of programs in basic materials (including rheological studies and piezoelectrics), as well as related work in vibration analysis and control applicable to the characterization of smart structures.

French government institutes, academic institutes, and private industry participate actively in European research initiatives relating to smart materials and structures. At this juncture, France does not appear as advanced in applying the technology as Germany, Italy, and the United Kingdom.

Germany is one of the European Union (EU) leaders in smart materials and structures, and an active participant in EU-sponsored programs. The United Kingdom also has a strong program in smart materials and structures, with participation from both academia and private industry. Participation in the Brite/EuRAM-sponsored activities pertinent to smart structures provides an insight into the breadth and depth of United Kingdom's capability.

Italy conducts substantial research in sensing and smart structures and activities involve several government, academic, and private industry participants.

Japan is frequently cited as being on a par with the United States as a world leader in smart materials and structures. Research areas of interest include smart polymeric composites with applications to infrastructures, ground, and aerospace vehicles; SMA materials and their composites; smart materials based on the coupling behavior between physical and mechanical phenomena; piezoelectric, piezoresistive, magnetostrictive, and their composite materials and structures where the stress and strain are key driving or resulting parameters; and novel electronic and optical composite materials with unique sensing capabilities.

In South Korea, both the Pohang University of Science and Technology (POSTECH) in Pohang (http://www.postech.ac.kr/e/) and the Seoul National University (http://www.snu.ac.kr/) conduct research in smart structures. The stated objectives of the research are to design and develop structures—especially for aerospace applications—that are adaptable and responsive to external disturbances.

In Switzerland, the work at the University of Lausanne covers a wide range of topics, including work in the bismuth titanate (BIT) family of piezoceramic materials (which are of interest for high-temperature applications) and in lead zirconate titanate (PZT) for high-frequency use.

DATA SHEET III-1.3. SMART COMPOSITE ROTORCRAFT STRUCTURES

Developing Critical Technology Parameter	Main rotor "smart" actuation of rotor controls yields reduced blade loading, vibration levels, and design complexity. Noise cancellation to reduce acoustic signature by 10 dB.
Critical Materials	Nitinol torsion actuators, active fiber composites (piezoelectric), piezoelectric stacks; high fatigue-strength embeddable electrical wire buses.
Unique Test, Production, Inspection Equipment	Production of piezoceramic actuator forms, including stacks, fiber composites, and single-crystal stacks and fibers.
Unique Software	Advanced rotor analysis software.
Technical Issues	Energy transfer to actuation system; use of lightweight actuators.
Major Commercial Applications	Variety of helicopters.
Affordability	Reduced maintenance costs.

RATIONALE

Smart material actuation has the potential of making on-blade control of rotor blades feasible and commercially viable. The structural properties of smart materials are not well known or documented, and their use in actuation devices has not yet been fully flight demonstrated. Preliminary tests and analyses have indicated the feasibility of using smart materials actuation on helicopter rotor blades. Higher harmonic control and individual blade control tests have demonstrated that it is possible to reduce (actively) helicopter rotor vibration and noise at critical flight conditions. The use of active rotor blades could lead to the removal of the need for swashplates. This would reduce weight and complexity at the rotor hub.

The Smart Materials Actuated Rotor Technology (SMART) program supported by the Defense Advanced Research Projects Agency (DARPA) considers active control of a rotor-blade trailing-edge flap and trailing-edge trim tab. Expected performance improvements for the flap include a 10-dB reduction in blade vibration-induced noise while landing; an 80-percent reduction in airframe vibrations; a 10-percent gain in rotor performance (L/D); and improved maneuverability from stall elevation. For the trim tab, the goal is to eliminate manual tracking requirements, relax blade-manufacturing tolerance, and reduce vibrations.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●●	Germany	●●●	Italy	●
Japan	●●●	Russia	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United Kingdom, DERA does a significant amount of research and experimentation in rotorcraft technology (http://www.dra.hmg.gb/dera.html). This research addresses the structural design of blades, model performance trials and evaluation, and validation of the theory and analysis of external noise research and structural acoustics, including noise path identification and advanced statistical energy analysis (SEA).

Scale rotor experiments are undertaken at a major hover test facility, where DERA also assesses rotor blade icing and the overall operational performance of rotorcraft. In addition, NASTRAN and DYTRAN finite element analysis, various pre- and post-processors, and STARS structural design optimization packages are available.

DATA SHEET III-1.3. STRUCTURAL PROGNOSTICS AND HEALTH MANAGEMENT (PHM)

Developing Critical Technology Parameter	A 20- to 40-percent reduction in maintenance manpower; 50-percent reduction in logistics footprint; 25-percent increase in sortie generation rate (compared with current aircraft).
Critical Materials	No materials issues, except those relating to high reliability sensors.
Unique Test, Production, Inspection Equipment	MEMS for integrated sensor and data processing.
Unique Software	PHM is a software-intensive system. Information processing methods including failure models that enable prognostics.
Technical Issues	PHM systems will need near zero false-alarm rate (hence, high-reliability sensors). Information-processing methods including failure models that enable prognostics. Wireless sensor systems are highly desirable. Capability to diagnose and isolate automatically, accurately, and consistently all faults within the avionics, propulsion, and subsystems.
Major Commercial Applications	Civil Infrastructure (bridges, dams, buildings, offshore oil rigs); helicopters; large, high-value equipment (e.g., large earth-moving equipment). Commercial aircraft can benefit by increased safety and reduced operating cost but will require major change in approach to structural integrity assurance.
Affordability	Affordable PHM system recurring costs will vary greatly with application. In all cases, cost savings will involve reduction of structural inspections. If PHM systems are not near 100-percent reliable, they will be unused in favor of the current manual inspection methods of ensuring structural integrity.

RATIONALE

PHM is a technology-maturation project focused on using advanced sensors integrated through algorithms and intelligent models, such as neural nets, to monitor, predict, and manage aircraft health. The JSF PHM system, in combination with the Joint Distributed Information System (JDIS), is designed to increase mission reliability and sortie generation rate, while decreasing maintenance effort and logistics footprint. The software-intensive systems are designed to use the newest technology to accomplish these goals. For example, JSF expects to use PHM technology to enable a 20- to 40-percent reduction in maintenance manpower, a 50-percent reduction in logistics footprint (in terms of numbers of C-141 cargo aircraft loads), and a 25-percent increase in sortie generation rate, along with an affordable 8,000 flight-hour service life. PHM is the only technology that can significantly reduce O&S costs associated with inspections while maintaining safety of flight and vehicle availability.

The goal of PHM is to enable what the JSF program calls autonomic logistics: a maintenance and supply system where information on aircraft faults detected while the aircraft is airborne is automatically downlinked to trigger the logistics system to meet the returning aircraft with appropriate parts, maintenance personnel, and maintenance equipment. Because both the individual aircraft PHM systems and the fleet-wide logistics system will include intelligent models (software with built-in learning capabilities), the system will eventually predict impending failures accurately and provide information about replacing parts just before they might fail (condition-based maintenance). Sensors for detection of composite failure, widespread (multisite) fatigue damage, and corrosion appear to be the key to the effective application of this technology. Sensor improvements in the following order of priority are necessary: reliability, cost, size, weight, and power.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	Denmark	●●●	France	●●●	Germany	●●●
Japan	●●●	UK	●●●●	United States	●●●●		

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

The lead application area for this technology has been for helicopters where the United Kingdom has made a significant commitment since the early 1990s. The United Kingdom is home to several of the world's leading manufacturers. Japan has a strong interest but is more oriented to civil infrastructure (rapid assessment of earthquake damage). Canada also has extensive research in this area. The Danish Companies, TERMA Information Systems Division (ISD) and IFAD, have joined the Boeing JSF One Team for PHM and will provide system design, information processing, and communications software.

DATA SHEET III-1.3. ACTIVE AEROELASTIC WING

Developing Critical Technology Parameter	Potential of up to 20-percent weight reduction.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	CFD tools.
Technical Issues	Include the integration of structural dynamics with multivariable reconfigurable control at levels that exceed current state of the art.
Major Commercial Applications	The commercial industry could make use of the technology for future transport development.
Affordability	The reduction of flight control surfaces and actuators produces savings in manufacturing and maintenance costs.

RATIONALE

The new technology that is developed will increase the ability of flight control systems to account for and use aeroelastic effects in a beneficial manner. Aeroelastic characteristics of the wing are used to enhance overall performance of the air vehicle. Unlike conventional approaches, control surfaces are employed to induce twist, causing the wing itself to produce control forces. Potential benefits include improved aerodynamic efficiency because of thinner wing design, increased control power with application of lower control forces, and decreased structural loads.

Limited commercial endeavors have been successful, but the technology needs a significant amount of maturation and development for military application.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●	Germany	●●	Japan	●●
Russia	●●●	Sweden	●●	Switzerland	●	UK	●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States, Boeing, NASA, and the Air Force are pursuing an active aeroelastic wing program. In a similar vein, researchers at the University of Michigan have developed a method to design single-piece, jointless mechanisms (compliant mechanisms) that may improve aircraft performance and simplify aircraft design by allowing aircraft wings without control surfaces (ailerons, slats, tabs, and so forth).

DATA SHEET III-1.3. ACTIVE LOAD/BUFFET ALLEVIATION FOR FLIGHT SURFACES

Developing Critical Technology Parameter	Aircraft service life extension of 20 percent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software to implement the developed algorithms.
Technical Issues	The problem involves the combination of traditional buffet-alleviation techniques with the optimal determination of control surface deflections that minimize or reduce the loads on control surfaces, thereby reducing the power required to drive the surfaces.
Major Commercial Applications	Commercial and military aircraft could benefit from this technology for the same reasons.
Affordability	Has the potential for life-cycle cost reduction via increased structural life.

RATIONALE

This technology uses advanced optimization algorithms to determine control surface deflections that provide the control power to accomplish the specified maneuver while simultaneously minimizing the structural loads placed on the aircraft.

This technology is applicable to all future aircraft, including JSF and UAV developments, and has the potential of being retrofit into current aircraft. Optimal solution of the combined load/buffet-alleviation problem involves significant computational resources. This development explores methods for determining the proper balance between model fidelity and computational resources but has the potential for life-cycle cost reduction via increased structural life.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●	France	●●●	Germany	●●●
Israel	●●●	Italy	●●	Japan	●●●	Russia	●●●
Sweden	●●●	Switzerland	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Any country with an active aircraft design industry would be expected to pursue this technology.

SECTION 1.4—AERONAUTICAL VEHICLE CONTROL

Highlights
• Optical technologies will become more prevalent for flight control system actuation and sensing.
• Multivariate, reconfigurable control systems will enhance survivability.

OVERVIEW

This section covers technologies associated with the control of air vehicles. Vehicle control systems are composed of sensors, computers, actuators, and other system components dictated by the architecture, methodologies, and algorithms required by an air vehicle in performing its intended mission.

Technologies critical to the development of future air vehicles include automated closed loop coupling; fly-by-light/power-by-wire (FBL/PBW), helicopter active control, multivariable reconfigurable control, and performance-seeking aircraft control. The requirement for control systems varies between manned air vehicles and UAVs. Some UAVs are meant to fly beyond current vehicle operational envelopes. MAVs introduce regimes that are not paralleled in full-sized vehicles.

In the future, the pilot will control an aircraft's situation via many real or virtual controls in a cockpit. In addition to the standard hand and foot controls, controls will be activated by head movement, eye movement, voice sensing, and brain activity (fly-by-thought).

Aeroelastic wings (see Section 1.3) are being investigated for the future. In this concept, the entire wing is a control surface. The former high alpha research vehicle (HARV) will be modified to research wing-twisting techniques for flight controls vs. traditional ailerons and flaps. Researchers want to determine if the twisting motion can make future wings lighter and aircraft more fuel efficient.

Flight-control technology defines the aircraft's flying qualities and the pilot interface. Helicopters are inherently unstable, nonlinear, and highly cross coupled. Advances in smaller, more powerful computers hold tremendous promise in this field to allow realization of the full potential of the rotorcraft's performance envelope and maintenance of performance, even in poor weather and at night. Integrating flight control with weapons control is of great interest to permit improved pointing accuracy and the use of lower-cost unguided rockets as precision munitions. Other goals include improved external load handling at night and increased exploitable agility and maneuverability.

RATIONALE

Future flight regimes for manned air vehicles and UAVs will require enhanced control systems. More functions will be controlled to achieve better system/subsystem performance. Adaptive/expert systems will enable maximum mission effectiveness and potentially reduce maintenance costs.

Objectives for new technology in fixed-wing aircraft include flight-control technologies leading to aircraft-control systems that:

- Automatically adjust to and survive combat damage
- Have on-board systems to identify flight control component failures and reduce repair time
- Provide supersonic tailless fighter control to improve range and payload
- Have FBL/PBW control technology to improve reliability
- Have LO air data systems to improve survivability
- Operate in poor visibility with an autonomous landing system to increase operational readiness.

For helicopters, the objective is to demonstrate, through simulation and flight test, later-generation rotorcraft digital FBW/light-control systems with fault-tolerant architectures (including carefree maneuvering), task-compliant control law, and integrated fire-, fuel-, and flight-control capabilities designed with robust control law design methods. This will allow improvements to all-weather/night mission performance, flight safety, and development time and cost.

WORLDWIDE TECHNOLOGY ASSESSMENT

Several countries are conducting R&D on aeronautical vehicle control. The United States, Russia, and the other European countries are most active. In the United Kingdom, DERA conducts high-fidelity experiments in flight and uses ground-based simulation, supplemented by in-depth theoretical studies, to improve simulation modeling and control law design. (See individual technology data sheets for worldwide technology assessments on specific technologies.)

LIST OF TECHNOLOGY DATA SHEETS
III-1.4. AERONAUTICAL VEHICLE CONTROL

DATA SHEET III-1.4. FLY-BY-LIGHT/POWER-BY-WIRE (FBL/PBW)

Developing Critical Technology Parameter	FBL: Reduce the weight of flight control system components by 50 percent by using optical wavelength division multiplexing (WDM) systems and sensors. PBW: A 5- to 25-percent reduction in subsystem weight over FBW aircraft.
Critical Materials	Fiber-optic materials.
Unique Test, Production, Inspection Equipment	Optical time domain reflectometers; optical spectrum analyzers; optical network analyzers; fiber-optic fault locators; splicing equipment.
Unique Software	Power system modeling and analysis to compare and evaluate possible architectures and topologies before hardware is actually built; modeling of converters, motor drives, actuators, starter/generators, batteries, and associated controls, and simulations of small systems and large end-to-end systems; signal conditioning and interpretation routines for fiber-optic sensors.
Technical Issues	Optical connectors and components operating in a tactical aircraft environment. WDM network test techniques will need to be adopted from the telecommunications industry.
Major Commercial Applications	Subsonic civil transports; high-speed digital data communications—telecom and datacom.
Affordability	Lower initial acquisition and direct operating costs, reduced weight, and the resulting increased aircraft performance and reliability.

RATIONALE

FBL technology is the replacement of electronic data transmission, mechanical control linkages, and electronic sensors with optical components and subsystems. PBW technology is the elimination of hydraulics, variable engine bleed air, and the constant speed drive for power generation through advances in aerospace power system technology. FBL/PBW technologies could provide lightweight, highly reliable, highly electromagnetically immune fiber-optic control systems, and all-electric secondary power systems for advanced subsonic civil transport aircraft. For an aircraft such as the F-16, the change to PBW could save up to 1,000 pounds of aircraft weight.

FBL systems offer the opportunity to develop safer, high-performance, lighter, and lower life-cycle-cost aerospace vehicles that are easier to build and maintain. The technology also offers advantages such as high-speed computing, large-bandwidth data transfer, increased sensor multiplexing, and improved reliability, plus immunity to electromagnetic interference (EMI), electromagnetic pulse (EMP), lightning, and high-energy radio frequency (HERF). In addition, optical fiber is fireproof and corrosion resistant.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●	France	●●	Germany	●●●
Israel	●	Japan	●●●●	Netherlands	●●	Russia	●●
Sweden	●	Switzerland	●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Any air-vehicle-producing country that is also developing fiber-optic networks for telephone communications has the capability and is probably looking into the use of fiber optics on aircraft. Most aircraft companies are pursuing FBL/PBW (with the FBL component being digital communications) with remote optical sensors powered by light, when feasible. Some European countries are attempting to develop adaptive/flexible systems that use WDM. Korea, Taiwan, Japan, and other Asian countries that are aggressively pursuing the fiber-optics telecommunications market are also likely to investigate the military applications.

Heriot-Watt University in the United Kingdom (with the Imperial College London, British Aerospace, and DERA) has investigated the use of fiber-ribbon-based optical data links, with the goal of delivering components and a complete system suitable for use in an FBL aircraft. Lucas Aerospace (United Kingdom) is developing FBL/PBW technology and is reported to have placed the first certified FBL-controlled system on an in-service aircraft (BAC-111). The German Aerospace Center (DLR), Eurocopter Deutschland (ECD), and Liebherr Aerospace Lindenberg (LLI) have finalized the design of a 60-million deutsche mark helicopter, which will be used to validate key technologies for future military and civil helicopter programs. The active-control technology, flying helicopter simulator (ACT/FHS) will be based on an EC135, refitted with FBL technology. Teijin Seiki Co., Ltd. (Japan) is actively conducting R&D aimed at realizing FBL technologies. In the United States, an F-18 systems research aircraft has been used to compare fiber-optic airframe and engine sensors with electrical ones. The F-22 will use an FBL control system developed by Lear Astronics. Moog Aircraft Group is also developing FBL technology.

DATA SHEET III-1.4. HELICOPTER ACTIVE CONTROL

Developing Critical Technology Parameter	A 60-percent improvement in weapons-pointing accuracy; a 50-percent increase in agility and maneuverability; a 30-percent reduction in flight control system flight test development time.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integration architecture; validation and verification software.
Technical Issues	Techniques for sensing the onset of envelope limits, cueing the pilot, and/or limiting pilot inputs; air vehicle math modeling for high-bandwidth flight control; flight control design, optimization, and validation techniques; optimum functional integration of flight control, weapon systems, and pilot interface.
Major Commercial Applications	Commercial rotorcraft.
Affordability	Reduction in major accident rate.

RATIONALE

Helicopter active-control technology (ACT) will integrate state-of-the-art rotorcraft flight control technologies while exploiting advanced fixed-wing hardware components and architectures. The intent is to produce second-generation rotorcraft digital FBL/light-control systems that have fault-tolerant architectures. Payoffs will include capability improvements in all-weather/night mission performance, flight safety, and development time/cost reductions. This technology will provide a 50-percent increase in agility and could be applied to all rotorcraft as system upgrades.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	France	●●●	Germany	●●●●	Israel	●●
Italy	●●	Japan	●●	Russia	●●●	UK	●●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●●● Moderate R&D ●● Limited R&D ●

DLR (Germany), the German Ministry of Defense, ECD, and LLI have designed a flying EC135 testbed that incorporates advanced rotor and FBL control technologies (along with state-of-the-art avionics concepts). They also have finalized the design of the combined ACT demonstrator/FHS. Ongoing research at DERA (United Kingdom) is defining the benefits of ACT in future military helicopters to achieve improvements in performance and reductions in attrition.

DATA SHEET III-1.4. MULTIVARIABLE RECONFIGURABLE CONTROL

Developing Critical Technology Parameter	Multivariable reconfigurable control is a key element in autonomous vehicle control and is necessary for safe vehicle operation. It will significantly reduce aircraft loss rates.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	COTS model-based development tools for developing and maintaining this technology.
Technical Issues	Transition of academic/theoretical technology to vehicle implementation is required.
Major Commercial Applications	Commercial aircraft would benefit through the increased safety benefit that the technology offers.
Affordability	Not an issue.

RATIONALE

The next generation of systems (e.g., aircraft, spacecraft, autonomous vehicles, missiles, and submarines) will be required to achieve and maintain the desired levels of performance under different perturbations and to perform multiple tasks in multiple operating regimes and under different failures. Multivariable reconfigurable control (inner loop) optimizes the available control power regardless of control effector failure or damage. Reconfigurable control compensates for control effector failure and/or damage and offers the potential for mission completion and safe return to base. This capability is essential for autonomous vehicle operation. The technology is applicable to all future aircraft and will benefit JSF preferred weapon system concept (PWSC) development. It is also a key technology for the successful operation of UAVs and UCAVs.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	China	●	France	●●
Germany	●●	Israel	●●	Italy	●	Japan	●●
Netherlands	●●	Russia	●●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A significant amount of work has been accomplished in this technology through the United States Air Force (USAF)/Boeing Reconfigurable Systems for Tailless Fighter Aircraft (RESTORE) program. Though much work is still to be done, flight testing has occurred for the tailless X-36 aircraft. RESTORE will also have application to large aircraft.

DATA SHEET III-1.4. PERFORMANCE-SEEKING AIRCRAFT CONTROL (PSAC)

Developing Critical Technology Parameter	In the maximum thrust mode: improvement in thrust (15-percent subsonic; 10-percent supersonic).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Performance-seeking algorithms are critical.
Technical Issues	Separation of feedback from noise.
Major Commercial Applications	Commercial aircraft can benefit from this technology.
Affordability	No added hardware is required for Adaptive Aircraft Performance Technology (AdAPT), making it very affordable.

RATIONALE

PSAC uses on-board models, real-time parameter identification, and advanced optimization and multivariable techniques to maximize vehicle performance. It is an adaptive, real-time, on-board optimization of engine, inlet, and horizontal tail position. PSAC was developed to optimize aircraft propulsion system performance during steady-state engine operation. The multimode algorithm minimizes fuel consumption at cruise conditions, maximizes excess thrust (thrust minus drag) during aircraft accelerations, extends engine life by decreasing fan turbine inlet temperature (FTIT) during cruise or accelerations, and reduces supersonic deceleration time by minimizing excess thrust.

This task requires the transition of academic and theoretical developments into practical application with the potential to maximize vehicle performance even for off-design flight conditions. This technology also applies to maximizing engine performance by accounting for inlet flow characteristics.

The greatest technical issue with the real-time PSAC system is the separation of feedback from noise. Feedback is a measure of the performance change caused by specific control input. For example, the flight control may droop the ailerons by 5 deg to determine if the resulting increase in wing camber reduces aircraft drag. Unfortunately, the resulting drag change is hard to measure because of signal noise, precluding the fight control from finding the optimal aileron control settings.

AdAPT is a research system flown onboard the NASA F-15 ACTIVE aircraft. It was used to determine optimum aerodynamic and engine control positions for a specific task. AdAPT overcame the noise problem by using fast Fourier transforms, which naturally reject noise. The AdAPT algorithm demonstrated the ability to measure changes in aircraft performance accurately and repeatedly and thus optimize all control settings in real time. The algorithm is readily transportable to any aircraft, with effectively no change required.

The high-stability engine-control (HISTEC) program, developed by Boeing and test flown on the NASA F-15 ACTIVE aircraft, is one example of PSAC. In that application, the engine management system used real-time parameter identification of engine distortion to prevent engine stall. This same technology can be applied to other flight systems in a similar manner to optimize vehicle performance. This technology is directly applicable to the JSF PWSC and to LO platforms, in particular those with compact inlet ducts.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●	Germany	●●	Japan	●	Russia	●●
Sweden	●	UK	●●	United States	●●●●		

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

Several PSACs have been flight demonstrated over the past 15 years in the United States. The latest example is the AdAPT flight demonstration, which was flown on the F-15 ACTIVE aircraft at NASA Dryden Research Center from 1996 through 1998. Several papers have documented the results of this program.

SECTION 1.5—AERONAUTICAL SUBSYSTEMS AND COMPONENTS

Highlights

- New subsystems and components technology will provide reduced air vehicle weight fraction, development costs, unit production costs, and O&S costs.
- Subsystem-level technology payoffs include an increase in mission reliability and a decrease in major accident rates.

OVERVIEW

Aircraft subsystems typically amount to about 10 percent of a fighter aircraft's empty weight and acquisition cost but cause more than 40 percent of aircraft equipment failures and downtime for repairs. Improvement in the latter factor will have a positive impact on the logistics requirement for maintenance and repair.

This section covers technologies used in air vehicle subsystems and components that include advanced air data, integrated vehicle management systems (VMSs), and MEMS.

RATIONALE

The goals for new subsystem technologies for fixed-wing aircraft are reduced air vehicle weight fraction, development costs, unit production costs, and O&S costs. Typical payoffs expected include a reduction in takeoff gross weight, an increase in payload, an increase in operational readiness, and a reduction in vulnerability. These payoffs lead to lower acquisition and O&S costs.

Technology barriers include management of a growing aircraft heat load with a shrinking aircraft heat sink; application of electric actuation to utility subsystems that require more power and higher actuation rates than are currently available, and development of mathematical models of complex physical processes for realistic modeling and simulation (M&S).

For rotary-wing aircraft, the objectives are to develop the subsystems technologies associated with advanced, digitized maintenance concepts and real-time, on-board integrated diagnostics. These technologies include piezoelectric, inductive, and optical sensors; statistical and neural network signal processing algorithms; high-speed databases and storage processes; and intelligent decision aids. A collective objective is to develop the hardware, software, and processes necessary to perform automatic detection of critical mechanical component failures and to reduce total maintenance labor.

These efforts contribute to rotary-wing vehicle system-level payoffs of an increase in mission reliability, a decrease in major accident rates, and a reduction in system O&S costs.

WORLDWIDE TECHNOLOGY ASSESSMENT

Several countries are conducting R&D on aeronautical subsystems. MEMS research is being funded around the world and holds great promise for subsystems application.

Several countries have capabilities of interest in subsystems for rotorcraft. Germany, Israel, and Japan have strong capabilities in advanced cockpit systems, but the German work on cockpit integration is of special interest. Germany is a recognized world leader in cognitive decision-aiding, knowledge-based systems, and high-speed data fusion. In addition, Japan has strong capabilities in avionics, based upon its world-class electronics capability. (See individual technology data sheets for worldwide technology assessments on specific technologies.)

LIST OF TECHNOLOGY DATA SHEETS
III-1.5. AERONAUTICAL SUBSYSTEMS AND COMPONENTS

DATA SHEET III-1.5. ADVANCED AIR DATA SYSTEMS

Developing Critical Technology Parameter	Provide air data at angles of attack > 35 deg.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software that will implement the algorithms and interface with vehicle control and redundancy management systems.
Technical Issues	Development of real-time model parameter identification and on-board model development; not constrained by personnel; commercial technology not geared toward military needs and requires significant development.
Major Commercial Applications	While advanced data systems are not currently used in commercial applications, the NASA Safety Initiative will explore this technology by using advanced air data estimation techniques to improve aircraft safety.
Affordability	Not an issue.

RATIONALE

This technology data sheet addresses air data systems beyond upgrades to current technologies (i.e., better computation, integration of current data, and so forth)

Exact and reliable air data are essential to the flight control systems in high-performance aircraft. Maximum maneuverability requires the accurate knowledge of flow angles and inertial accelerations. Also, conventional flow sensors loose their effectiveness at angles of attack greater than 35 deg. Advanced air data systems are needed for controlled, post-stall flight. These new systems will enable the expansion of the flight envelope to extreme angles of attack and include an optical, laser-based flow-measurement system or a Flush Air Data System (FADS), where pressure ports are mounted flush in the aircraft nose. The real-time flush air data-sensing system concept is being evaluated for possible use on the X-33 and X-34 reusable space-launch vehicles.

All LO vehicles will benefit from this technology, which eliminates the requirement for obtrusive air data probes. For platforms such as the JSF, this technology will reduce hardware requirements and life-cycle costs by providing an algorithmic level of redundancy necessary for safety of flight. The technology is also applicable to failure detection and isolation systems, operations at high angle of attack, and hypersonic flight conditions.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●	Germany	●●●●	Israel	●●
Japan	●●	Russia	●●●	Sweden	●●	Switzerland	●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

NASA is developing an advanced air data system using the F-18 systems research aircraft. Daimler-Chrysler Aerospace AG (Germany) is also working on advanced air data systems for the X-31 and the Eurofighter.

BACKGROUND

In early Shuttle experiments, FADS was a concept that proved to be a valuable tool in hypersonic flight testing. FADS is one of the key technologies being demonstrated by the X-34. The LoFLYTE® test bed aircraft[2] was used to test new aerospace technologies, including Accurate Automation's Neural Air Data Sensor subsystem.

[2] The LoFLYTE® vehicle was the first known powered flight of a hypersonic waverider configuration at low speed.

DATA SHEET III-1.5. ENERGY-MANAGEMENT SYSTEMS (EMSs)

Developing Critical Technology Parameter	Fully integrated subsystem integration.
Critical Materials	High-temperature insulation, advanced composites, and lightweight metallic materials; phase change materials; cryogens.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	On-board software for optimized performance; M&S software for validation and verification of multiple subsystems.
Technical Issues	Seamless integration of models from disparate sources (air-vehicle designers, subsystem designers, and customer-furnished equipment). The ability to use this technology successfully is constrained by the lack of qualified technical personnel who have a working understanding of multiple, dissimilar disciplines. Enhanced heat-transfer systems are in early stages of development. Successful integration and exploitation of multiple heat sinks requires extensive modeling, controls integration, and performance integration.
Major Commercial Applications	Helicopters; any heat-transfer application requiring either a large quantity of heat dispersion or significant temperature reductions from high-power density applications.
Affordability	Reduced parts count.

RATIONALE

An EMS seeks to optimize the supply of energy (electrical, thermal, fluid flow) to subsystems in the appropriate quantity and condition and at the appropriate time based on flight conditions and operator commands. EMS development must begin at the outset of the air-vehicle design. At this time, the energy needs of each system must be determined to design common and multiple-user energy conversion devices such as electrical power supplies. The intent is to reduce or eliminate the prior practice of having an energy conversion device built into each subsystem. The aim of EMS is to reduce the space, weight, and power needs for subsystems.

Military applications provide the cornerstone for fully integrated subsystems. To deploy smaller systems with comparable performance levels successfully, a significant amount of effort will be required. Extensive coordination between engine companies and the platform integrators will be required.

While an increase in system performance has always been a lofty goal, this objective has recently been coupled with a growing need to decrease the volume requirements. These objectives “pull” the candidate solutions in different directions. For example, as systems become smaller, the available volume for utility functions also decreases. Only through the integrated installation of multiple systems will an optimal solution be possible. This technology integration will provide for increased superiority for military platforms.

Very-high-heat flux systems are not currently available for high-power-density applications. As emerging technologies continue to increase with respect to power densities, the resulting thermal management problems will continue to escalate. By dramatically enhancing the thermal management systems with improved heat transfer materials, more and more capabilities will be available for insertion within the combined military and high-technology commercial arenas. As such, phase-change materials that can be combined with existing systems present a singular opportunity for thermal management improvements and provide an enabling function for order-of-magnitude changes for future growth capabilities. The technology is new and is a key enabler for enhanced thermal management applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	France	●●	Germany	●●●	Israel	●
Japan	●●	Russia	●●	Sweden	●	UK	●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The JSF program has the lead in the United States. Daimler-Chrylser Aerospace AG (Germany) is investigating integrated VMSs for future aeronautical systems (Eurofighter, X-31).

DATA SHEET III-1.5. MICROELECTROMECHANICAL SYSTEMS (MEMS)

Developing Critical Technology Parameter	No quantitative parameters are available. The concept is to use extremely small (micron size) devices to perform similar tasks, albeit at a smaller scale, of conventional machines.
Critical Materials	Semiconductor materials.
Unique Test, Production, Inspection Equipment	Semiconductor manufacturing equipment.
Unique Software	None identified.
Technical Issues	Fabrication and packaging challenges because some aircraft applications require exposure to severe environments.
Major Commercial Applications	Inlet duct flow control and structural health monitoring.
Affordability	Significantly reduces aircraft vulnerability and increases aircraft survivability. MEMS fabrication is less expensive than traditional devices.

RATIONALE

Currently, MEMS are being applied to sensor technology and navigation equipment. However, many other applications for MEMS are emerging (e.g., inlet duct flow control and structural health monitoring). Other applications of MEMS have the potential to reduce aircraft vulnerability and increase aircraft survivability significantly, thereby requiring fewer aircraft.

A microfabricated fuel atomizer is under development. This atomizer offers better performance and is less expensive than conventional metallic devices and may be used in future gas-turbine combustors. Low-temperature MEMS under development at NASA Lewis Research Center include pressure-, heat-flux-, and strain-sensor arrays on flexible substrates. A MEMS ice detector will provide icing data on surfaces that were impossible to monitor with conventional sensors.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●	France	●●	Germany	●●●
Japan	●●●	Netherlands	●●	South Korea	●●	Sweden	●●
Switzerland	●●●	UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

MEMS are being developed throughout the world. Those countries/organizations listed below are only a sampling of MEMS researchers/developers. For a more complete list, see Section 12.5, Production Equipment. The MEMS research locations shown do not necessarily indicate that the research is destined for use in air vehicles.

- ***Canada***

  LISA, a laboratory of the Engineering Physics Department of École Polytechnique of Montréal, which is an affiliated school of Université de Montréal, is researching MEMS and micro-machining.

- ***Germany***

  Researchers at the Berlin Technical University Microsensor and Actuator Technology (MAT) Center, Berlin, are developing high-temperature (up to 500 °C) pressure sensors that can be operated in combustion engines.

Accurately monitoring and controlling the pressure and temperature in the combustion chamber, can raise engine efficiency and reduce fuel consumption and pollutant emission.

- ***Netherlands***

  MESA+ Research Institute, University of Twente is conducting MEMS research as is the Delft Institute of Microelectronics and Submicron Technology (DIMES) at Delft University of Technology.

- ***Switzerland***

  The Institute of Microtechnology, University of Neuchâtel, Switzerland, has had work underway for 15 years on microsensors and microactuators, optical MEMS, microfluidics, and other MEMS technologies.

SECTION 1.6—AERONAUTICAL DESIGN AND SYSTEMS INTEGRATION

Highlights
• Systems integration is a key in taking existing technologies and using them in new, improved ways.
• Improvements in design integration technology are essential in the development of complex systems.
• Nearly simultaneous design processes are enabled by analytical tools coupled with high-speed computer networks.
• Design and integration simulations will reduce development, maintenance, and repair costs.
• On-board health monitoring systems will improve time between removal and replacement of components.

OVERVIEW

This section covers technologies that enable the integration of various aeronautical technologies covered in other sections into a mission-ready, affordable air vehicle. It includes vehicle and manufacturing process design methods and technologies for the pilot to interface with an aircraft. Integration technology is information based and has become more viable because of advanced analytical tool developments, such as structural finite element methods, CFD, and advanced database management. Computer graphics have also been used, and this avoids expensive physical mockups of new aircraft. Design teams are able to couple analytical tools with high-speed computer networks and data management to work nearly concurrently with each other and to exchange critical design information.

RATIONALE

Integration of the numerous technologies required in an aeronautical system is possibly more important than the individual technologies themselves. The maximum impact of the total system may not be realized if integration is not properly accomplished with other systems and the pilot/crew. The increased emphasis on affordability causes cost and interdisciplinary optimization to become essential. Computer applications allow the identification of trade-offs between mission performance and system cost, the development of alternative designs, the elimination of unsuitable designs earlier in the process, the definition of cost/benefits of applying new technologies, and increased chances of initial production successes. A nearly simultaneous design information system can help to keep design efforts coordinated. One area does not proceed too quickly without feedback from others.

The aims of design and integration technologies include reductions in production cost for the first aircraft, in O&S costs, in engineering and manufacturing development (EMD) costs, and in airframe weight and increases in aircraft performance.

WORLDWIDE TECHNOLOGY ASSESSMENT

Many countries are conducting R&D on aeronautical design and integration. The United States, Japan, Russia, and other European countries are most active. (See individual technology data sheets for worldwide technology assessments on specific technologies.)

LIST OF TECHNOLOGY DATA SHEETS
III-1.6. AERONAUTICAL DESIGN AND INTEGRATION

DATA SHEET III-1.6. ADVANCED EXTERNAL VISION

Developing Critical Technology Parameter	No quantitative parameters are available. However, the intent of this technology is improved field of view and display of the external environment under conditions too degraded for the human eye.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Equipment for improved image registration and system boresighting.
Unique Software	Software for image blending and matching (required software currently exists in prototype and/or crude fashion).
Technical Issues	Worldwide database availability and updates. Computational power. Multisensor (or multicamera) tiling. Special sensor housings, alignment fixtures and procedures, and position monitoring require unique technical approaches. Image blending/fusion. Achieving desired perceptual veridicality and image realism.
Major Commercial Applications	Ground operations for commercial aircraft; possibly image presentation for game applications.
Affordability	Not an issue.

RATIONALE

The intent of this technology is to increase pilots' ability to see outside the aircraft. In military applications, it increases ability to see and destroy targets and to detect and counter threats. In commercial aircraft, it improves ground maneuverability. For transatmospheric high-speed vehicles, such as HSCT, it would replace heat-intolerant window structures. The same technology, or parts of it, could serve as a direct view replacement and be the display of choice for remotely operated underwater vehicles or, in some applications, for unmanned aircraft operations.

For full field-of-view coverage, or in cases where wide field is combined with high-resolution requirements, multiple sensors will be required. For aircraft applications, multiple sensors with overlapping fields are also required for system redundancy/reliability. Combining these inputs may include color adjustment on a sensor-by-sensor basis, image realignment, and image blending for fully or partially overlapping images. Further, images from on-board sensors may have to be processed with stored database information. This is a major software technology (i.e., image processing/computational) technical issue.

An area of concern is in the display of the external imagery. There are numerous possible approaches, including helmet-mounted displays (HMDs) and fixed, large-area displays. Head and possibly eye tracking will be required if the helmet approach or if variable-resolution fixed displays are used. Regardless of the hardware approach for image presentation, challenging issues include the perceptual veridicality desired and the display techniques to produce the correct level of perceptual realism. Some COTS software from gaming applications could be applied.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●●	Germany	●●●	Israel	●●●
Japan	●●●●	Russia	●●	UK	●●●	United States	●●●

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

Parts of this technology are being worked by the virtual reality (VR) and gaming communities. Sensor designers, aircraft manufacturers, and image processing firms are also working the technology. The level of funding, however, has decreased in recent years.

DATA SHEET III-1.6. AIRCRAFT DESIGN AND SYNTHESIS TOOLS

Developing Critical Technology Parameter	Reduction in overall aircraft design cycle time can be achieved by applying higher order analysis methods in a multidisciplinary design environment for configuration synthesis.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Optimization procedures.
Technical Issues	Optimizations of analysis codes for vehicle synthesis.
Major Commercial Applications	Commercial aircraft can benefit from this technology.
Affordability	Not an issue.

RATIONALE

This task requires the integration of advanced optimization software with higher order analysis codes to improve the vehicle synthesis. Commercial industry has not developed the technology to the extent necessary for military application.

NASA proposed an initiative for a new intelligent synthesis environment to develop a future design environment for engineering and science mission synthesis. One part of this was rapid synthesis and simulation tools (RSSTs), which has as its objective the development of synthesis and simulation capabilities necessary to predict life-cycle product and system response and performance. Intelligent, ultrafast, and accurate physics-based computational methods—deterministic and nondeterministic—will be developed using soft computing methods. These non-traditional design tools will incorporate artificial intelligence (AI) methodologies, such as neural networks, genetic algorithms, and fuzzy logic. These capabilities support the collaborative design environment for the synthesis of science, engineering, and technology development.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●	Germany	●●	Israel	●●
Japan	●●	Russia	●●	UK	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Optimization software is available commercially, and countries involved in indigenous aircraft development have the advanced analysis routines available. Development of the knowledge required to merge these technologies is a competitive advantage to be maintained. The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology conducts a significant amount of research related to aeronautics.

DATA SHEET III-1.6. MICRO AIR VEHICLE (MAV)

Developing Critical Technology Parameter	Size: less than 15 cm (6 in.) in length, width, or height; weight: 50 grams or less; capable of staying aloft for 20 to 60 minutes for a range of 10 km; low aspect ratio wings at Reynolds numbers as low as 10,000.
Critical Materials	Lightweight composites.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Flight control algorithms.
Technical Issues	Flow physics and aerodynamics at very low Reynolds numbers; weight/volume of payload; power consumption; propulsion; affect on the environment.
Major Commercial Applications	Air monitoring; rescue; inspection and maintenance of equipment at inaccessible locations; agriculture.
Affordability	Relatively inexpensive.

RATIONALE

MAVs are fully functional, militarily capable, 6-degree-of-freedom aerial robots whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location where it can perform a variety of missions. Reconnaissance and surveillance of sites of interest without being detected or observed are basic military needs. Electronic surveillance and detection equipment can now be miniaturized so that entire payloads are measured in grams. Other missions could include chemical-biological agent detection and characterization and urban battlefield communications enhancement. Now needed are miniature aircraft that will fly for up to 60 minutes, be able to transmit sensed information or record, and return to a base site. Speeds of the MAVs will be low (on the order of 25 to 35 mph).

The MAV requires a highly integrated design of the air vehicle and the payload. This requires knowledge of the vehicle and the sensor suite. Various designs employing fixed wing, rotary wings, and flapping wings are being investigated. Propulsion involving electric motors and stored electrochemical energy is limited by battery energy density. The energy stored in chemical reactions, such as oxidation, has the potential for much greater energy output per unit mass than current electric storage cell technology. Nontraditional propulsion schemes, including reciprocating chemical muscle (RCM) (flapping wings) for actuation, hold promise for near-term success.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	Germany	●●	Italy	●
Russia	●	UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Many countries are pursuing this technology. Most prominent are Australia, Canada, Germany, Russia, the United Kingdom, and the United States. In the United States, programs are run or sponsored by DARPA, the Naval Research Laboratory (NRL), NASA, the Jet Propulsion Laboratory (JPL), and various universities. U.S. companies/organizations leading the R&D efforts involving fixed and rotary wing MAVs and propulsion systems include AeroVironment, Inc., Simi Valley, California, whose Black Widow MAV stays aloft for half an hour using high-energy lithium batteries; Sanders, a Lockheed Martin Company, Nashua, New Hampshire; Lutronnix Corporation, Del Mar, California; Micro Craft, Inc., San Diego, California; the Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts; D-STAR Engineering, Shelton, Connecticut; Technology in Blacksburg, Inc., Blacksburg, Virginia; IGR Inc., Beechwood, Ohio; M-DOT Inc., Phoenix, Arizona; and Aerodyne Corporation, Billerica, Massachusetts.

In addition, other U.S. companies/organizations that have been at the forefront of MAV R&D involving an entomopter, or flapping wing, technology include the Georgia Tech Research Institute (GTRI), Atlanta, Georgia; SRI International, Menlo Park, California; Vanderbilt University, Nashville, Tennessee; and the California Institute of Technology, Pasadena, California,

The International Society of Structural and Multidisciplinary Optimization (ISSMO) has held yearly MAV competitions since 1997. The objective of the competition is to design, build, and fly a very small "Micro" aerial vehicle capable of flying a distance of 600 m from the launch site to the target, capturing the image of the target, and delivering that image to the officials at the launch site—all in 45 minutes. The main emphasis is on the use of multidisciplinary design optimization (MDO) methodology in the design of this vehicle. Participants (either reports or entries in the competition) have included MLB Company (United States), Politecnico Di Milano (Italy), the University of Florida, Arizona State University, the University of California (Santa Barbara), and Mississippi State University.

DATA SHEET III-1.6. SINGLE-STAGE-TO-ORBIT (SSTO) REUSABLE LAUNCH VEHICLE (RLV)

Developing Critical Technology Parameter	Reduce cost to low earth orbit (LEO) from $10,000 per pound to $1,000 per pound.
Critical Materials	Carbon-carbon; aluminum-lithium composite liquid oxygen tank.
Unique Test, Production, Inspection Equipment	X-33; X-34.
Unique Software	Aerodynamic databases.
Technical Issues	Scaling up technologies; integration; unconventional engines; composites.
Major Commercial Applications	Commercial space access.
Affordability	Expensive program ($4–10B) that will yield an order-of-magnitude reduction in cost to orbit.

RATIONALE

RLVs would provide rapid access to space and supporting missions, such as space control (protecting friendly space vehicles and inspecting and/or destroying adversary vehicles) and on-demand reconnaissance and surveillance and perhaps attack.

Figure 1.6-1. X-33

The X-33 (see Figure 1.6-1) is a fully automated, fully functional, half-scale version of an operational RLV called VentureStar. The propulsion, the propellants, aerodynamics, and the operations of these two RLV are the same. These similarities allow tracing the performance of the various technologies and design elements from X-33 to VentureStar. When the technology is successful in the X-33, the components will be scaled up to construct a VentureStar vehicle. In November 1999, one of the two composite X-33 liquid-hydrogen tanks failed a structural test, and this has led to an undefined delay in the flight test program.

The X-34 (see Figure 1.6-2) will be used to demonstrate key technologies that can be used in a reusable launch vehicle. These technologies include composite primary and secondary airframe structures; composite reusable propellant tanks; cryogenic insulation and propulsion system elements; advanced thermal protection systems and materials; low-cost avionics including differential GPS integrated GPS/Inertial Navigation System (INS); integrated vehicle health monitoring system; and a flush air data system. They also provide a platform for demonstration of “Added On” or additional experiments.

Figure 1.6-2. X-34

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Japan	●●	Russia	●●●	United States	●●●●

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

In Japan, the NAL has conducted concept studies on an SSTO aerospace plane. In Europe, Daimler-Chrysler is working on an RLV known as Hopper, a sled-launched, runway-recovered two-stage-to-orbit system that uses an expendable upper stage. Hopper is based on the Vulcain II L2/LOX engine of Ariane 5.

DATA SHEET III-1.6. “HEALTH” MONITORING AND DIAGNOSTICS

Developing Critical Technology Parameter	Reduction in “Could Not Duplicates” and “False Alarms” from levels of 30–50 percent to the levels of 5–10 percent; prognostics for mechanical systems that avoids mission aborts and reduces unscheduled maintenance by as much as 25 percent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Advanced sensors to detect component operation and performance deterioration.
Unique Software	Signal processing to detect anomalies and signatures of degraded systems; fusion/integration algorithms to combine multiple sensor outputs; open software architecture to integrate development tools and provide a run-time framework that can be easily updated with mature algorithms and new technology.
Technical Issues	This task needs to transition theoretical/academic developments into industry application and integrate together the health monitoring and diagnostics of air vehicles. Open hardware and software architecture and standards are needed to leverage a sizable commercial technology base. Wireless communications devices and inexpensive, reliable sensor technology are issues. There is no obvious shortage of personnel or skilled labor for development. Automation vs. skilled labor to interpret and act on system output is an issue.
Major Commercial Applications	Commercial aircraft will benefit from this technology by supporting condition-based maintenance, notifying pilots about the cause of aircraft behavioral anomalies (diagnostics), and providing information needed by reconfigurable flight control systems. Nearly every industry with electromechanical devices uses and needs this technology, including processing plants, automobiles, aircraft, and construction/mining equipment. The processing plant, automotive, and heavy machinery manufacturers are technology drivers because of the large volume.
Affordability	Low-cost sensors and plug-and-play software are the central issues here because they would reduce the support costs of air vehicles.

RATIONALE

This technology is used to monitor aging of the aircraft. Health monitoring and diagnostics provides information concerning current aircraft operating state, including the ability to forecast impending failures in the structural, propulsion, or flight systems. Upon occurrence of noncatastrophic failures/damage, the system will identify the nature of the failure for a pilot or ground-based operator. The same information will allow the vehicle reconfigurable control system to adjust to the failure, and the integrated system will assess the extent to which the failure affects overall aircraft performance. The technology is applicable to JSF and all future aircraft (manned and unmanned). The technology is also an integral part of the NASA Safety Initiative, which is being developed to reduce the commercial accident rate.

This technology increases the mission reliability of vehicles and reduces support costs. Applications to flight-critical systems are of particular interest. These include turbine engine, flight controls, subsystems (e.g., fuel) and structures. Several DoD-sponsored programs involve commercial and military partners.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●●	China	●●●	France	●●●
Germany	●●●	Japan	●●●●	Netherlands	●●	Russia	●●●
Sweden	●●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Nearly all developed countries have some effort to develop this technology. Automobile, equipment, ship-building, factory automation/equipment manufacturers, and aircraft manufacturers are pursuing technologies related to this subject.